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Journal

of

THE ROYAL AERONAUTICAL SOCIETY

SEPTEMBER 1956

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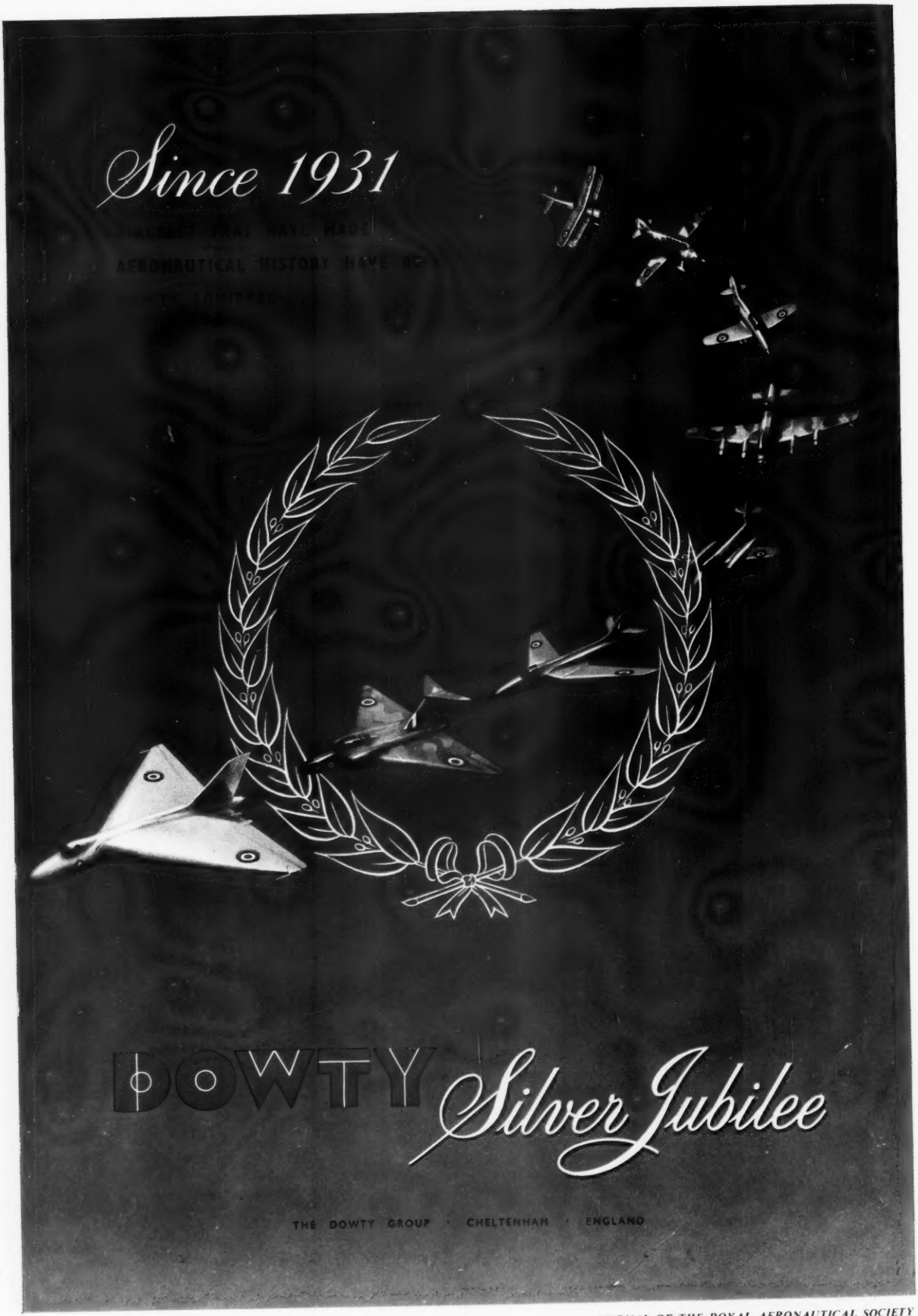
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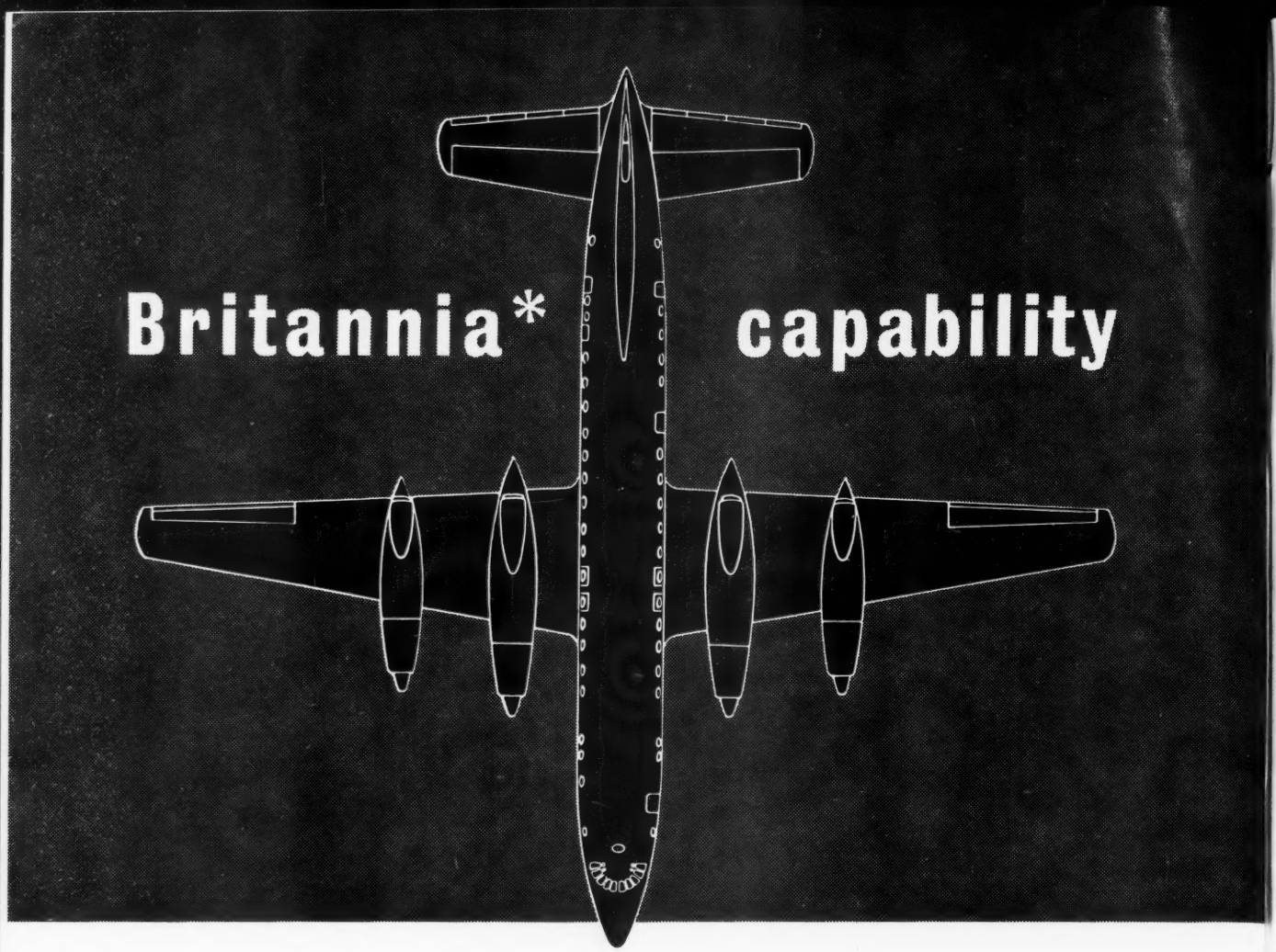

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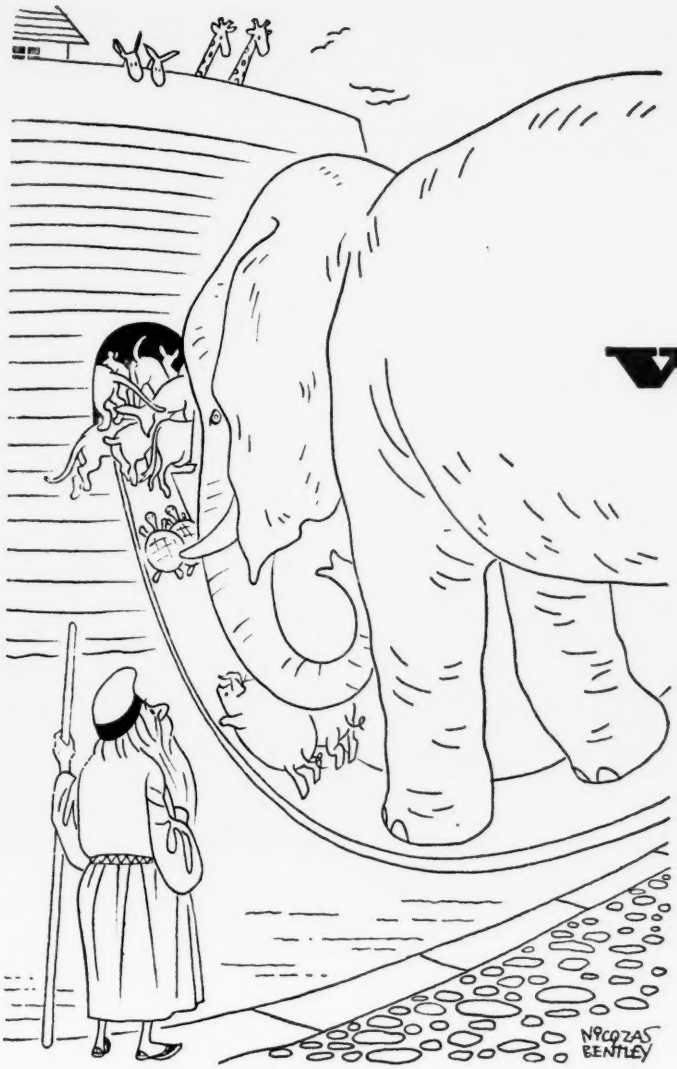

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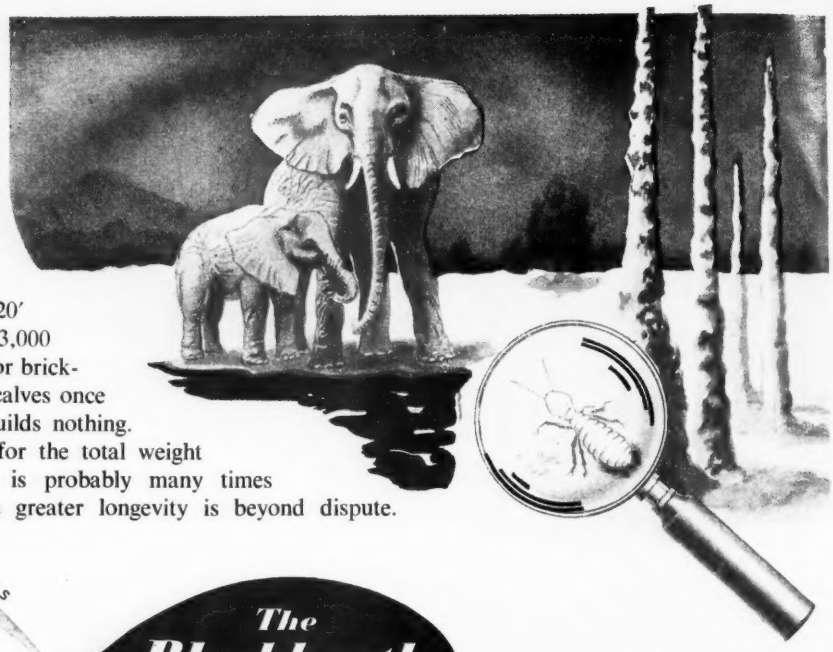

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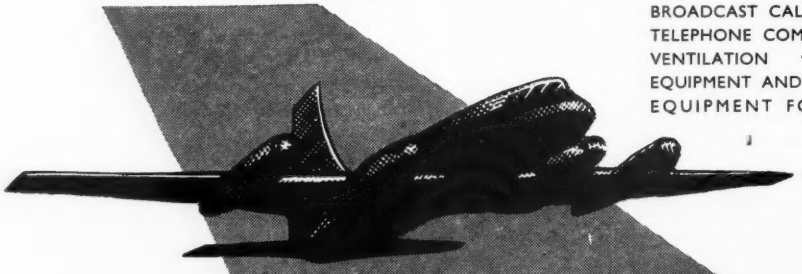

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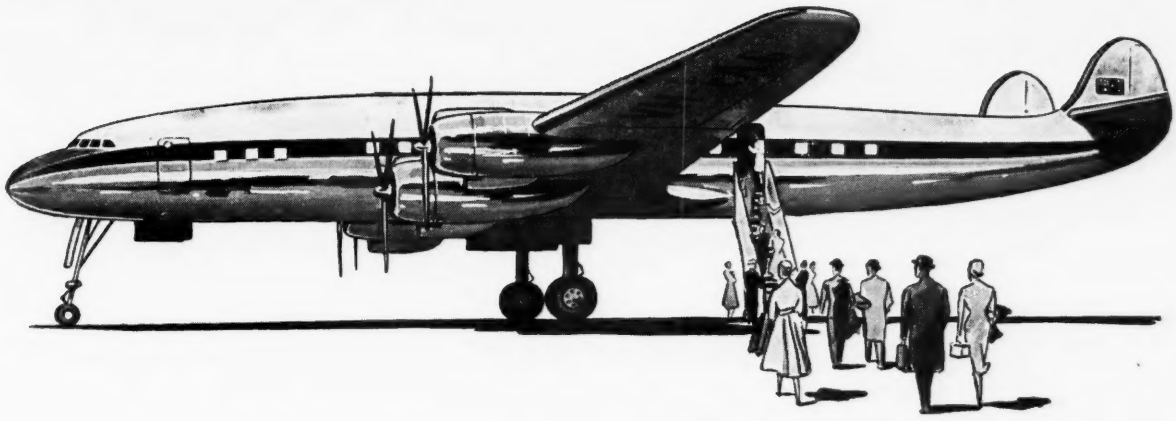

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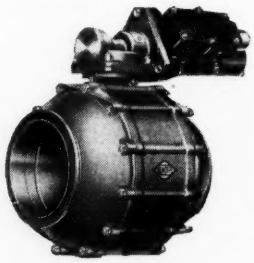

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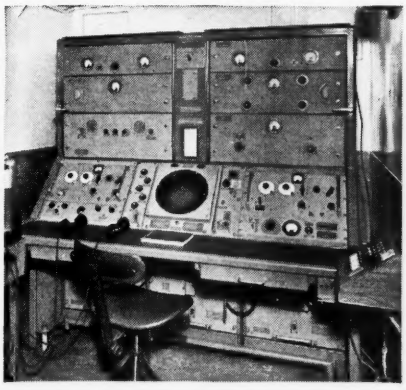

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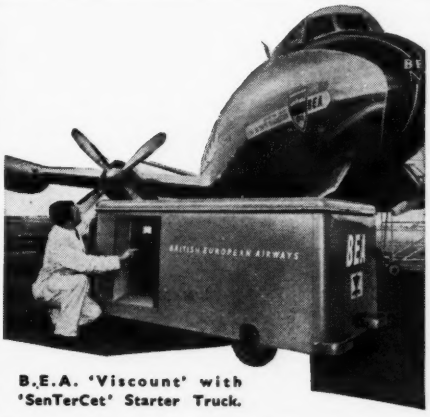

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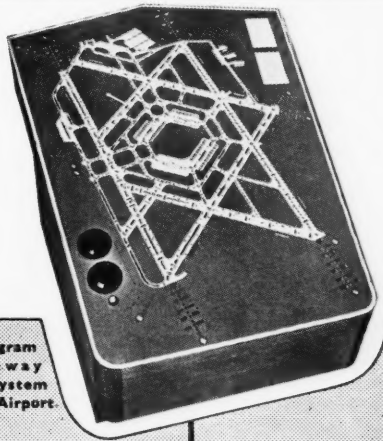

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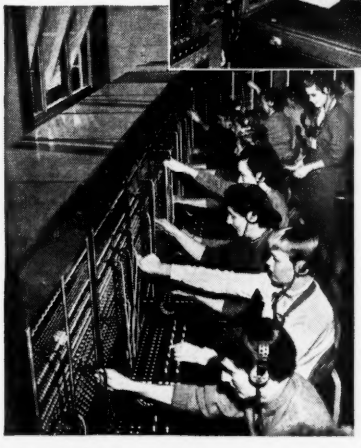

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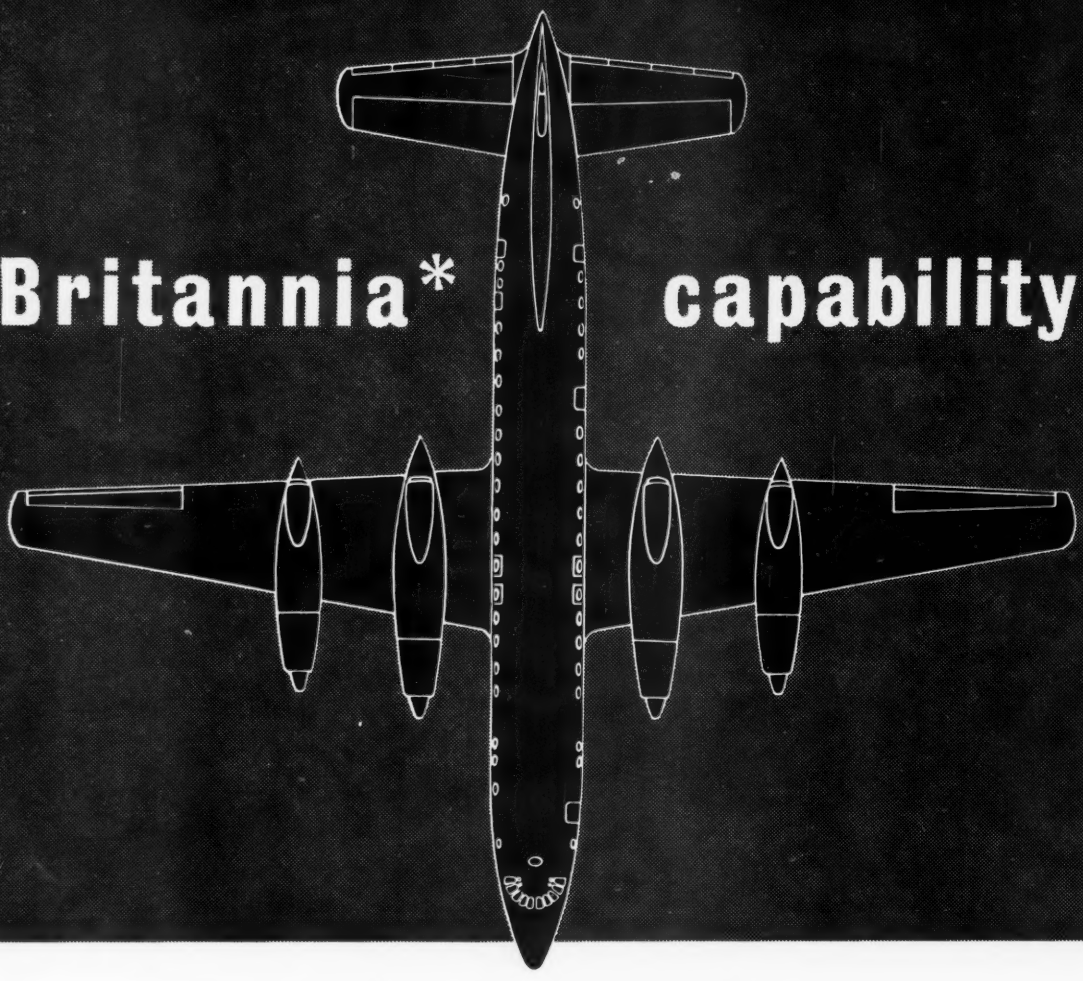

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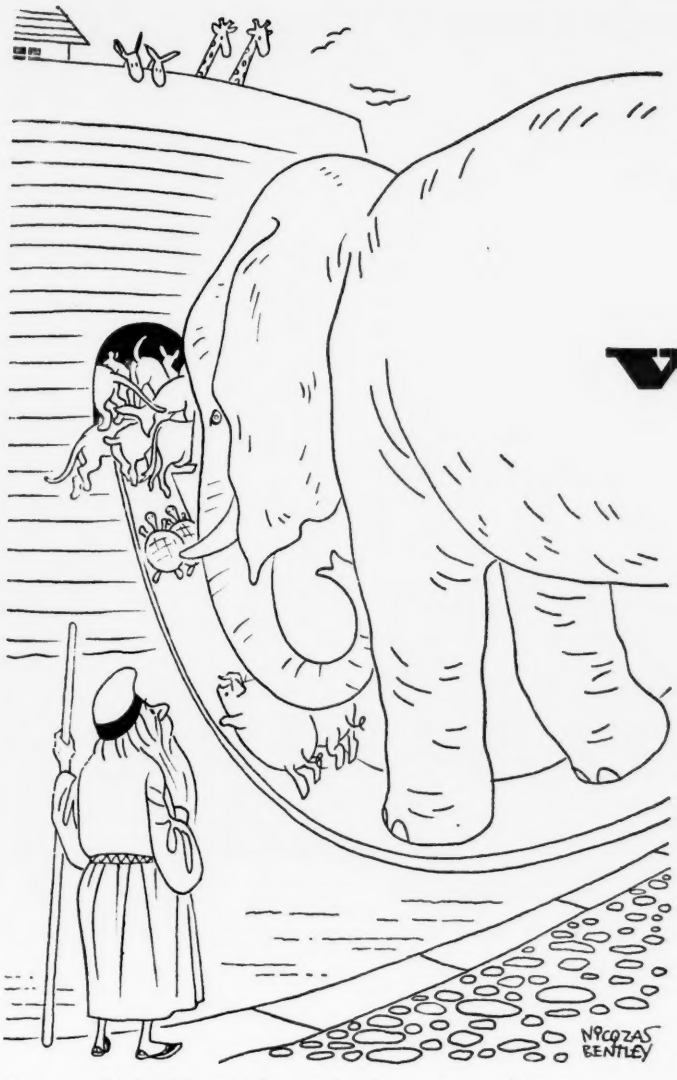

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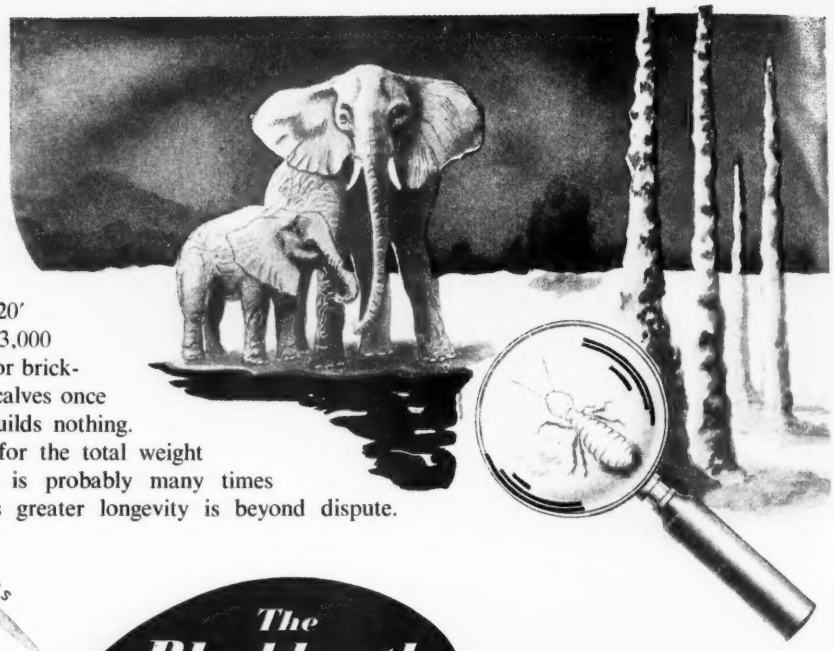

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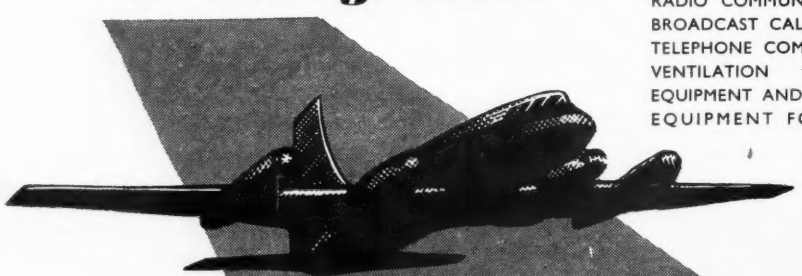

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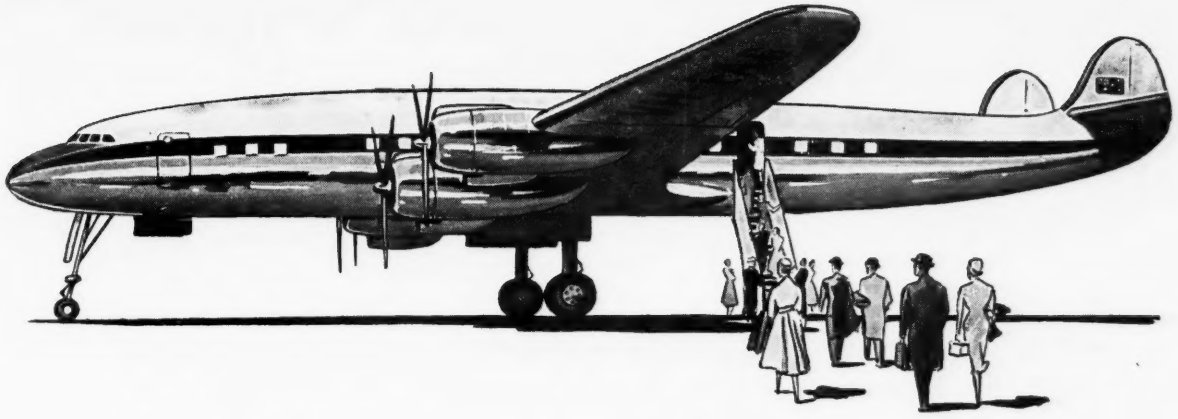

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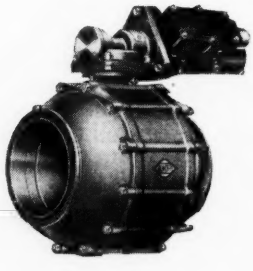

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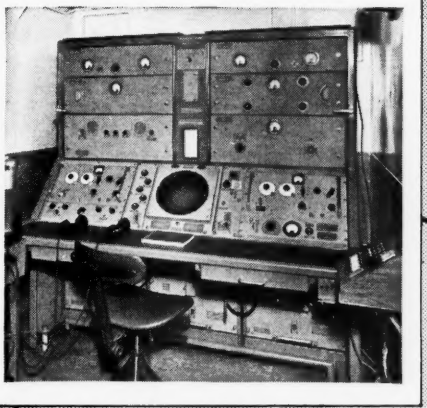

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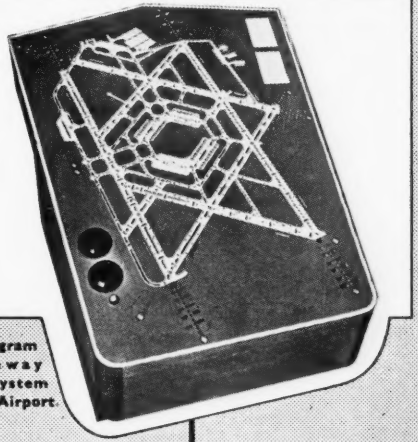

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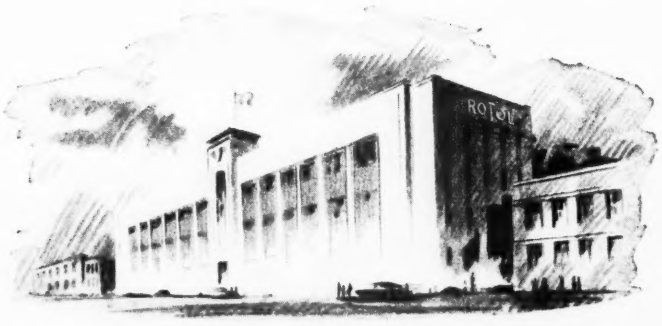

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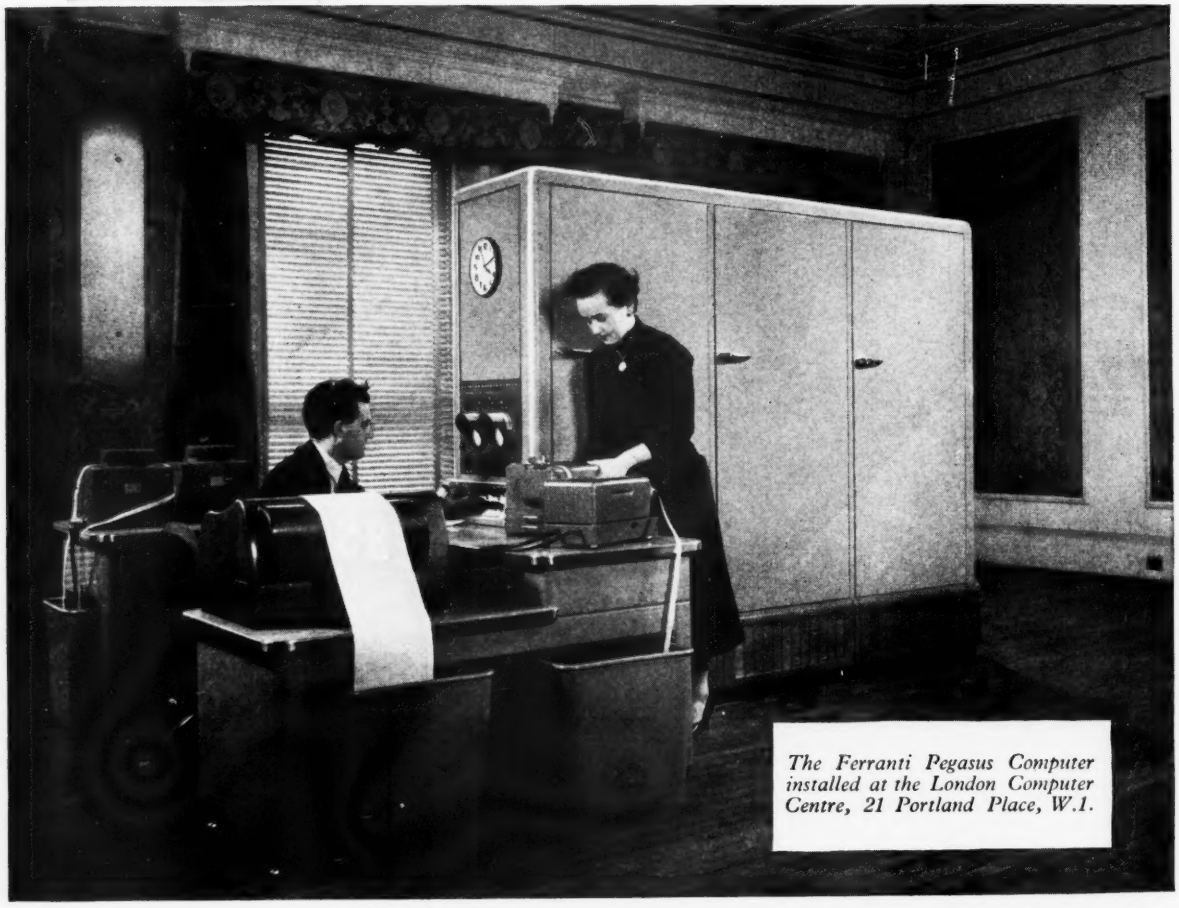

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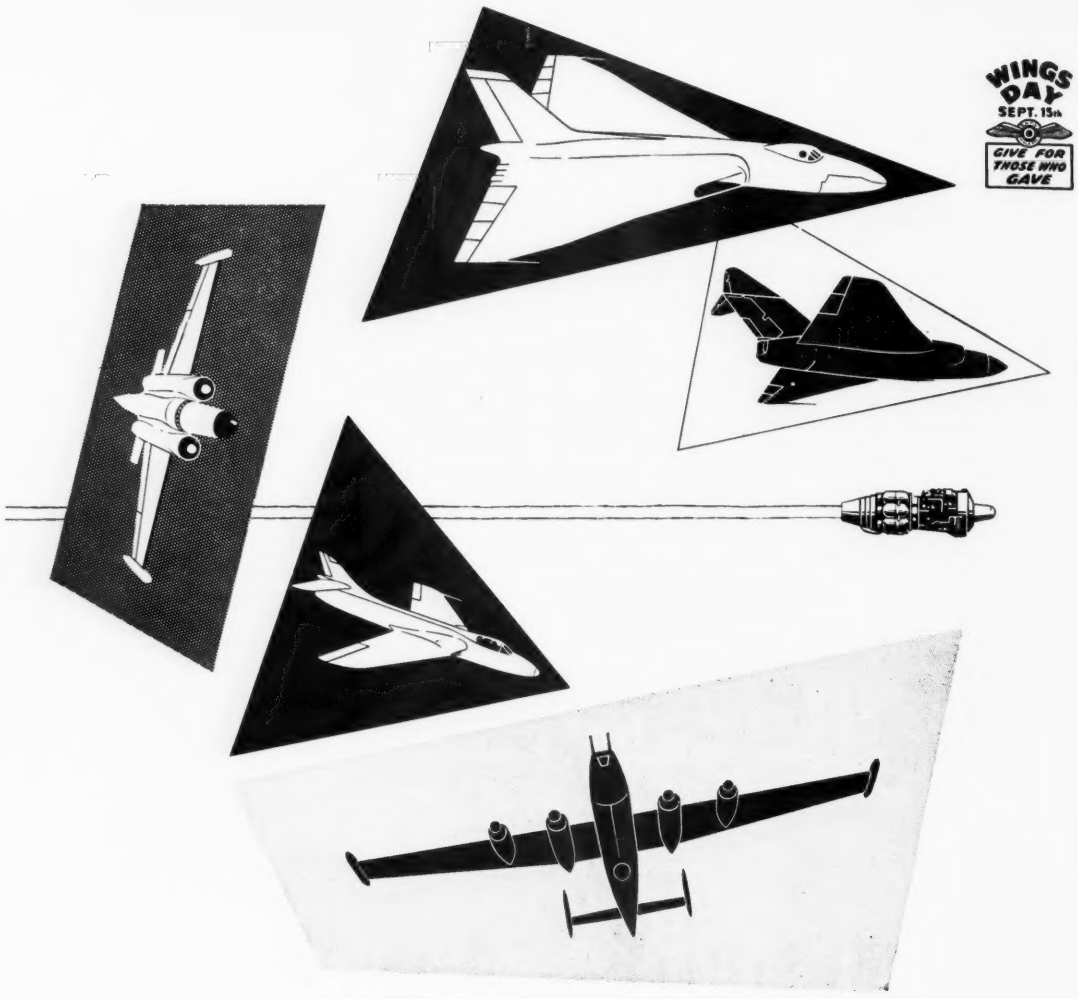

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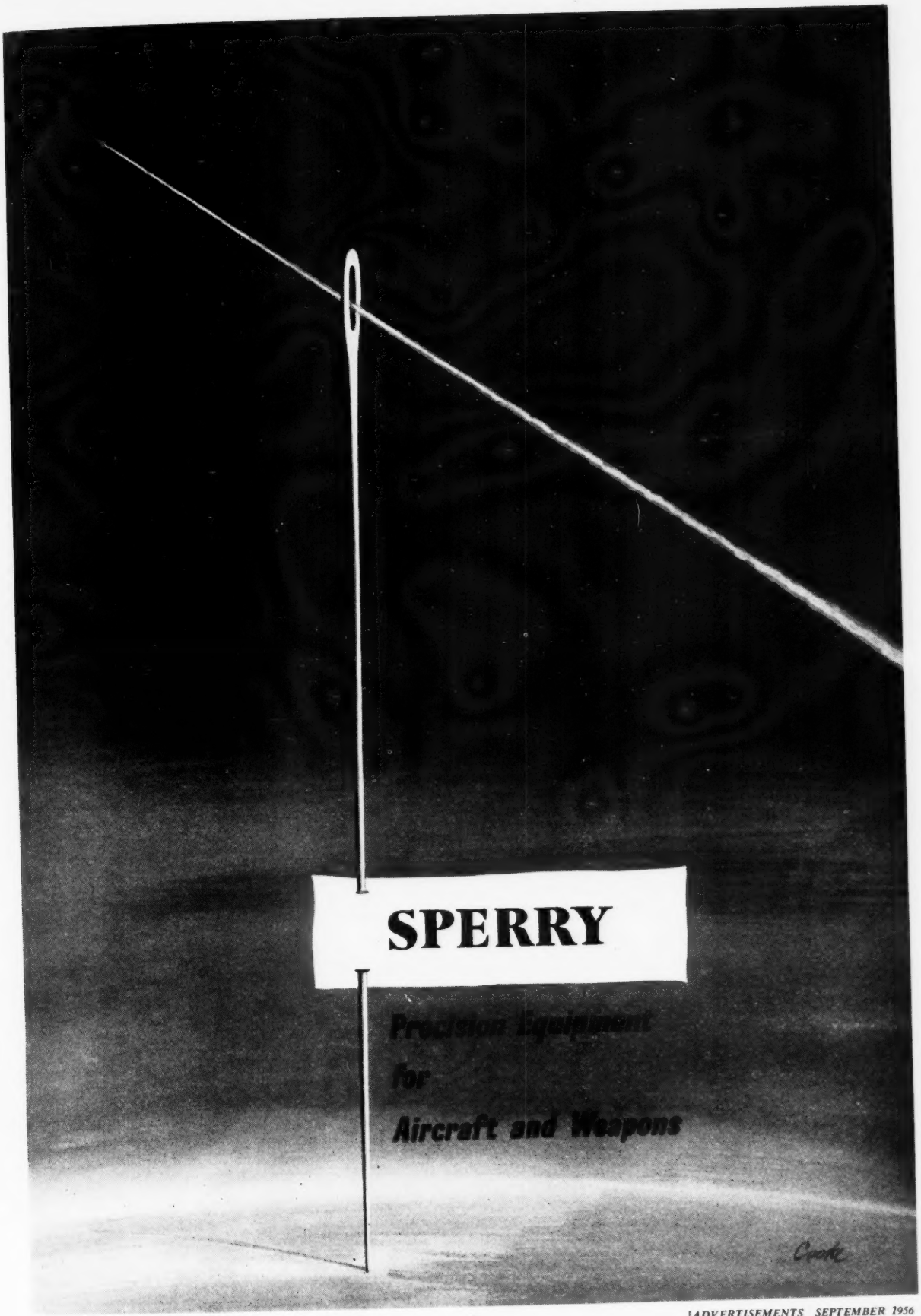
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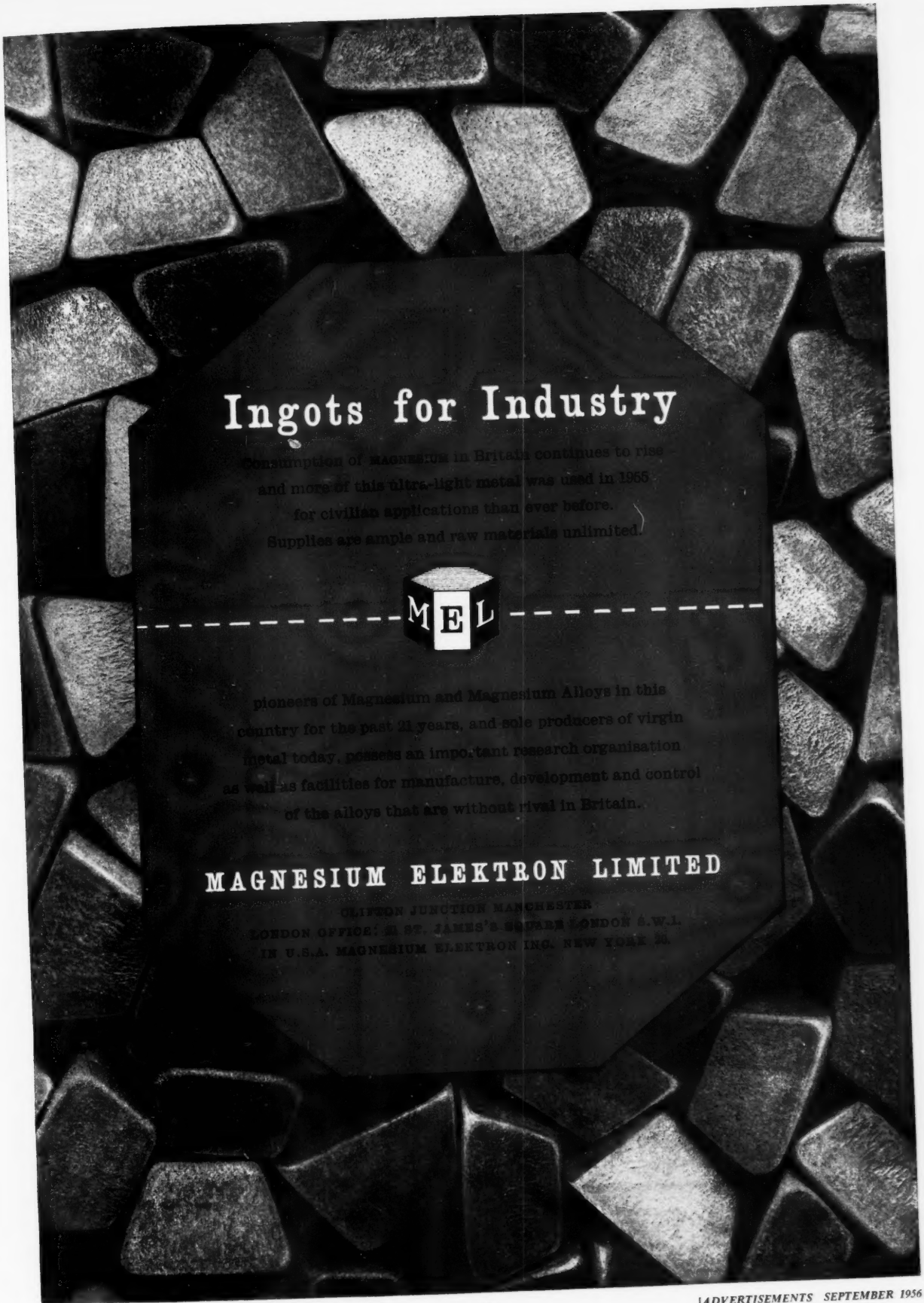
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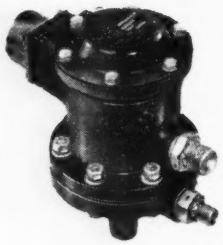
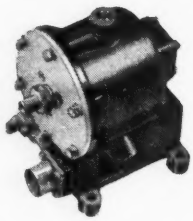
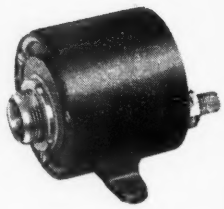


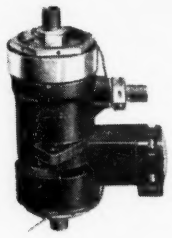
Type PAF
Dual setting, high fuel pressures.



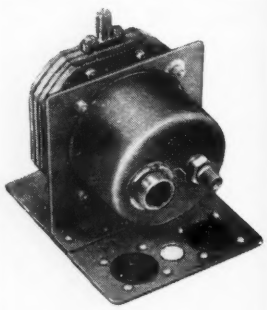
Type FKS
Differential fuel pressure.



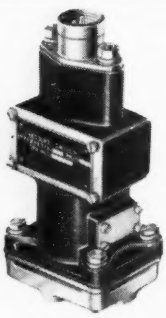
Type PAD Altitude.



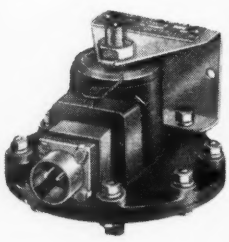
Type FGY Fuel pressure.



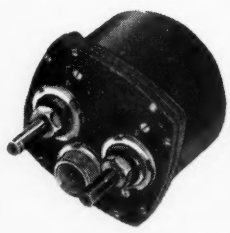
Type FKK
Differential air pressure



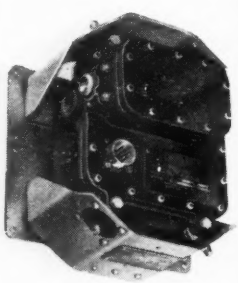
Type FKY
Air and selected liquids.



Type FGW Ram air pressure



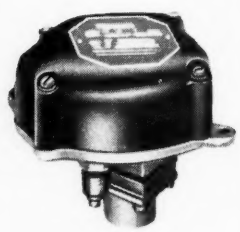
Type PAC Mach Number.



Type FLY Pressure ratio.

Type FOM Oil pressure.

Type FKY
Air and selected liquids.



Type FPH Hydraulic pressure.

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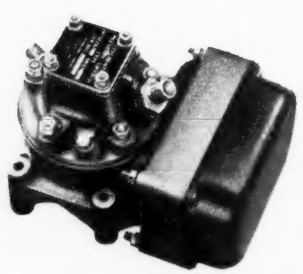

Type FOF Dual setting, low air pressures

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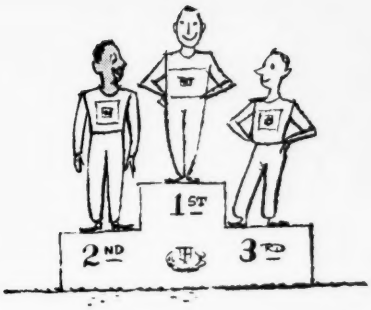

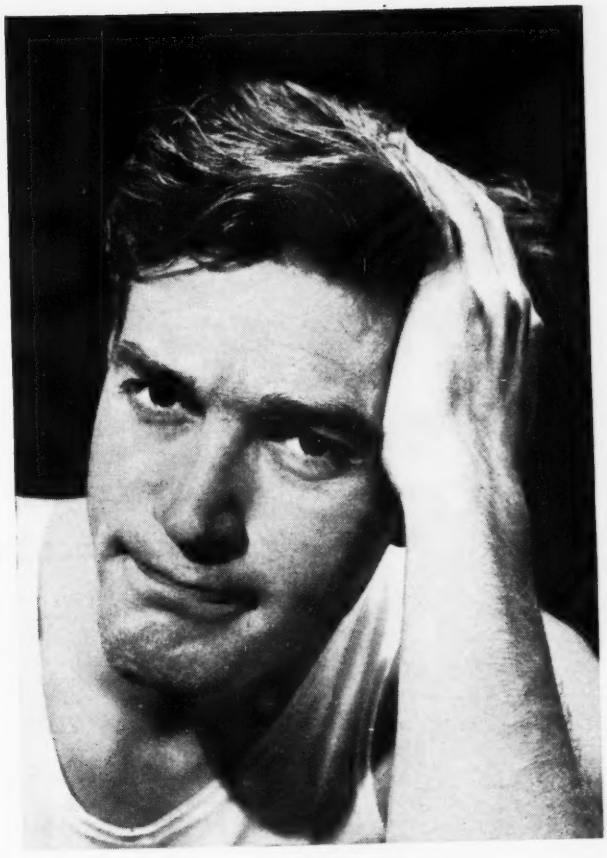

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"Almost every operating record has been smashed by the VISCOUNT"

—extract from "Capitaliner" magazine of Capital Airlines Washington D.C.

The following facts are taken from Capital's first statement of Viscount operating costs. Period: July '55 - April '56, during which the fleet was built up from 3 to 19 aircraft.

Break-even Load Factor (All costs) 56·8%

Actual Load Factor 80%

The factor for costs directly related to the running of the aircraft was 25·5%. This was achieved with a utilization of 6·5 hours per day. Both direct and indirect costs at full utilization of 8·5 hours per day (already achieved in May) should result in a break-even factor of 53% - 55%.

Repeat order for 15 VISCOUNTS

The release of these figures has been followed by the announcement of a repeat order for 15 Viscount 700D aircraft by Capital Airlines. The total number of Viscounts in service or on order for Capital is now 75

With little over half the seats sold VISCOUNTS make profits

Passenger load factors of 80% and over are being reported by most other airlines operating Viscounts. It is believed that these figures represent the highest sustained passenger load figures ever attained by an airliner.

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Four Rolls-Royce Dart Propeller-turbine Engines

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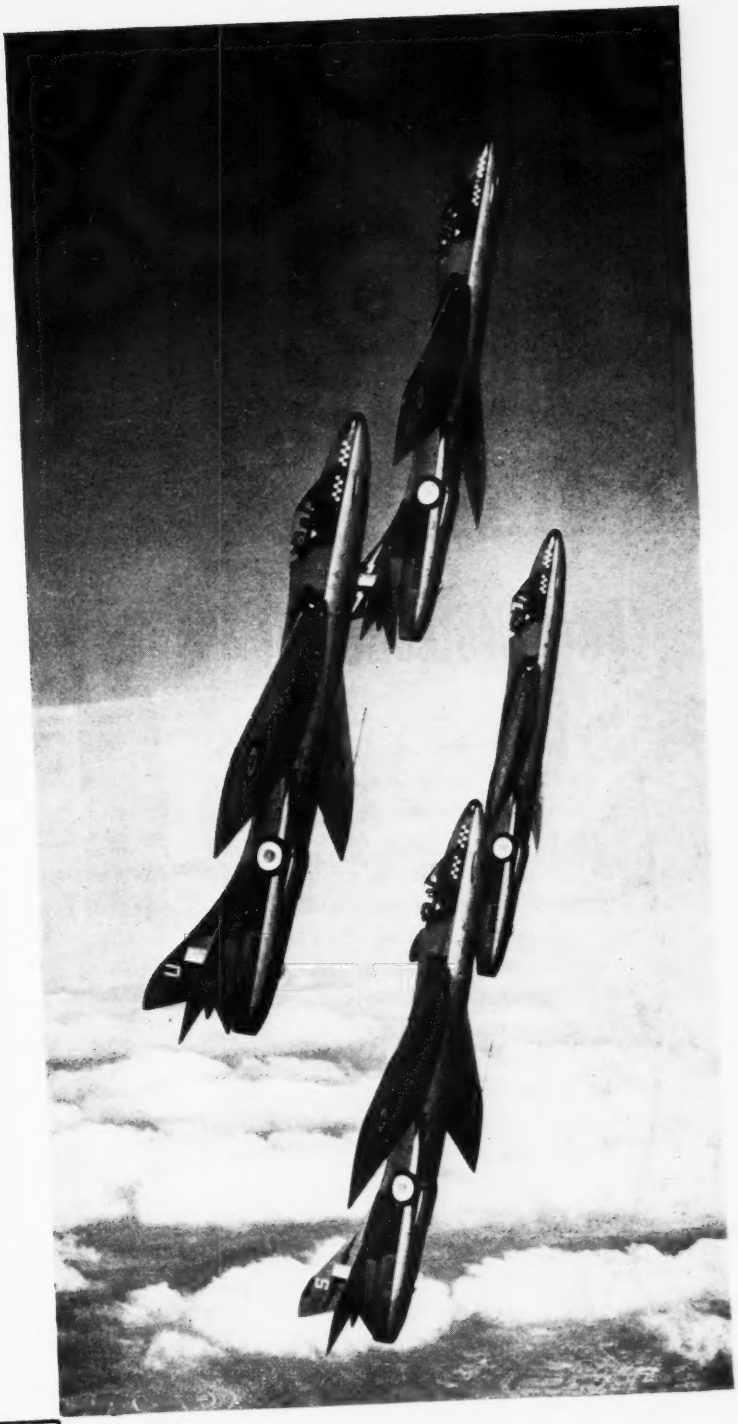
Photograph by courtesy of Gloster Aircraft Co. Ltd.



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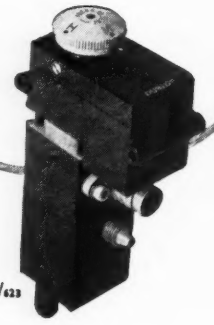

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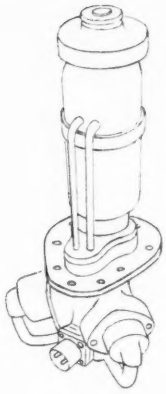
VALVE VERSATILITY



In the aircraft industry, not all design advances are spectacular. Relatively unseen improvements make a vital contribution to aviation progress. Such a contribution is a new approach to fuel system requirements evolved recently by Flight Refuelling Ltd., pioneers of pressure refuelling.

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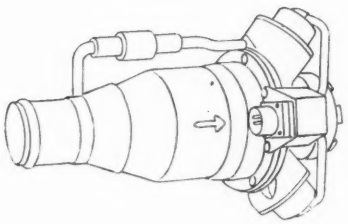
Right: *Mark* 29 **In-line Dual-purpose Valve** Similar to the Mark 27, but with the transfer side of the valve servo-operated by independent float mechanism so that in the event of electrical failure the valve will automatically close to prevent air transfer to engines.



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Machining a wing spar web from a single aluminium alloy plate. Photograph by courtesy of Vickers-Armstrongs (Aircraft) Ltd.

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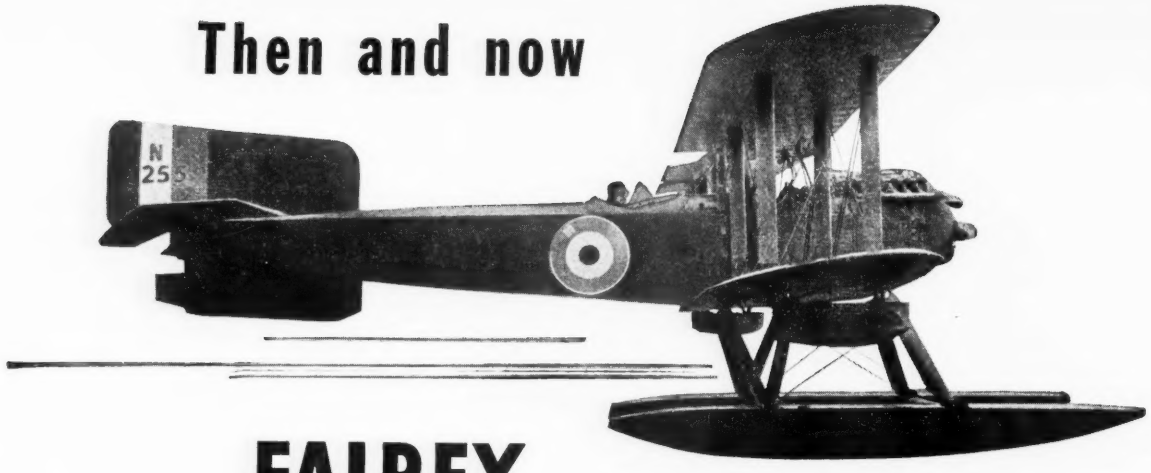

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September 1956

NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

News of Members

Squadron Leader J. Anstess (*Associate Fellow*) has now been posted to a Research and Development appointment in the Structures Dept. of the R.A.E.

P. H. F. Burton (*Associate Fellow*) has resigned from the position of Project Engineer at Handley Page, Reading Limited, and has taken up a position of Chief Production Engineer, at the Bristol Aeroplane Co., Cardiff.

Handel Davies (*Fellow*), now Scientific Advisor to the Air Ministry, has been appointed Deputy Director-General Aircraft Research and Development (Future Systems), M.O.S., from October.

S. F. Follett (*Associate Fellow*), Deputy Director General of Aircraft Equipment Research and Development, is to succeed Mr. S. Scott-Hall as Head of the Ministry of Supply Staff of the British Joint Services Mission in Washington in October.

R. W. Fowkes (*Associate Fellow*) is now employed as a Technical Representative with the Esso Petroleum Co. Ltd.

L. G. Frise (*Fellow*) has left Hunting Percival Aircraft Ltd. where he was Technical Director and Chief Engineer.

L. W. Johnson (*Associate Fellow*) has been appointed Assistant Manager of the Development and Research Department of the Mond Nickel Co. Ltd.

S. L. Kochanski (*Graduate*) has been appointed a Lecturer, Department of Aeronautics, Imperial College.

Wing Commander J. R. C. Lane (*Associate Fellow*) formerly Director of Technical Services, Pakistan Air Force, has now been appointed Service Manager to Irving Air Chute of Great Britain Ltd.

J. H. Paul (*Graduate*) is now working for Avro Aircraft Ltd., at Malton, Ontario.

J. Przybylski (*Associate Fellow*) has left Pametrade Research Station, Hallsend to take up a post in the Steam Turbine Design Department of the English Electric Co., Rugby.

L. J. Stephenson (*Graduate*) has relinquished his post as a Senior Design Engineer with The Plessey Co. Ltd., and joined Anthony Hoists Ltd., Ruislip, as a Project Engineer.

A. Stone (*Associate Fellow*) has joined Solar Aircraft Co. as Aerodynamicist at the Company's San Diego plant.

W. J. Trotman (*Associate Fellow*) has taken up an appointment as a Senior Design Engineer with the Lockheed Aircraft Corporation, Marcetta, Georgia, U.S.A.

H. G. Wenham (*Associate Fellow*) formerly with the British Joint Services Mission in Washington has taken up an appointment as Ministry of Supply, Resident Technical Officer at the de Havilland Engine Co. Ltd., Stag Lane.

D. H. Whaley (*Associate Fellow*) has resigned his position of Deputy Manager, Patents Department, Rolls-Royce Ltd., and is now with the Bristol Aeroplane Co. Ltd.

Acknowledgments

The Council wishes to thank H. F. Cowley, Esq., *Companion*, for a copy of "Our Flying Men" by Mrs. Maurice Hewlett, and T. D. Sills, Esq., *Associate Fellow*, for "Life Sketches and Photographs of Flying Men" (The Blackpool meeting of 1910).

They also thank B. S. Shenstone, Esq., *Fellow*, for Forschungsbericht Nr. 195 Des Wirtschafts-und Verkehrsministerium Nordrhein-Westfallen.

Baden-Powell Memorial Prize

The Baden-Powell Memorial Prize, awarded to the best candidate in Part II of the Associate Fellowship Examination, has been awarded to Mr. B. Gumpel.

British Nuclear Energy Conference

The British Nuclear Energy Conference has been formed by the Institutions of Civil, Mechanical, Electrical, and Chemical Engineers and the Institute of Physics. The five societies will arrange for the presentation of papers dealing with nuclear energy and the Board of the Conference proposes to promote national and international conferences from time to time. It will also publish a Journal about four times a year containing records of the papers, discussions, symposia and conferences conducted by the Board.

A Symposium on the Calder Works Nuclear Power Plant will be held at the Institution of Civil Engineers on 22nd and 23rd November 1956 when Sir John Cockcroft and Sir Christopher Hinton will be among the speakers. Members of Societies other than those sponsoring the new organisation of the British Nuclear Energy Conference may attend this symposium and application forms may be obtained from Mr. A. McDonald, The Secretary, B.N.E.C., 1-7 Great George Street, London S.W.1.

Associate Fellowship Examination Results

The following Candidates were successful in the Associate Fellowship Examination held in June 1956:—

Part I—London

D. O. Challis, Strength of Aircraft Materials and Theory of Structures; D. H. Chester, Aerodynamics; D. W. Cocking, Theory of Machines.

Flight Cadet G. G. Jones, Aerodynamics.

D. W. Howe, Thermodynamics.

B. Rothnie, Strength of Aircraft Materials and Theory of Structures.

P. G. Simpkins, Aerodynamics.

D. W. Wingate, Physics.

Part II—Old Syllabus—London

Miss R. B. Fox, Aerodynamics.

B. Gumpel, Strength of Materials and Theory of Structures. (Awarded Baden-Powell Prize.)

E. T. Harris, Aerodynamics.

J. F. Leigh, Strength of Materials and Theory of Structures.

C. Russell, Aircraft Design.

Part II—Outside London

C. G. Brown (Hull), Engine Design; J. D. Burley (Hull), Aerodynamics.

D. A. Drinkald (Hull), Engine Design.

G. McGuire (Preston), Strength of Materials and Theory of Structures.

H. Phillips (Preston), Strength of Materials and Theory of Structures.

Part I—Abroad

Wing Commander S. D. Amin, I.A.F. (Kanpur), Pure Mathematics, Mechanics, Thermodynamics, Theory of Machines.

Flt./Lt. B. Husain (Karachi), Physics, Aerodynamics.

H. R. Satyanarayana (Mysore), Strength of Aircraft Materials and Theory of Structures.

G. S. Uppal (Delhi), Pure Mathematics, Mechanics, Physics.

Part II—Old Syllabus—Abroad

C. S. Krishnamoorthi (Mysore), Strength of Materials and Theory of Structures.

T. L. Narasimhan (Mysore), Engine Design.

B. N. Vaman Rao (Mysore), Engine Design.

DIARY

LONDON

1st October

MAIN LECTURE AT DERBY BRANCH.—The First Sir Henry Royce Memorial Lecture.—Sir Henry Royce, Bart. H. I. F. Evernden, M.B.E. Rolls-Royce Welfare Hall, Nightingale Road, Derby. 6.15 p.m.

9th October

SECTION LECTURE.—The Pressure Jet Helicopter. A. Stepan. Library, 4 Hamilton Place, London, W.1. 7 p.m.

11th October

MAIN LECTURE AT HENLOW BRANCH.—Rocket Motors. S. Allen. Building 62, R.A.F. Technical College, Henlow. 8 p.m.

17th October

MAIN LECTURE.—The Importance of Time in Aircraft Manufacture. Air Cdre. F. R. Banks, C.B., O.B.E. The Institution of Mechanical Engineers, Birdcage Walk, London, S.W.1. 6 p.m. (Tea 5.30 p.m.)

GRADUATES' AND STUDENTS' SECTION

22nd September

Visit to the National Physical Laboratory, Teddington.

28th September

Novel Methods of Take-off and Landing. T. J. Cummings. Library, 4 Hamilton Place, W.1. 7.30 p.m.

10th October

Service Flight-testing of High-speed Aircraft. Sqn. Ldr. P. D. Thorne. Library, 4 Hamilton Place, W.1. 7.30 p.m.

17th October

Visit to the Royal Aircraft Establishment, Farnborough.

BRANCHES

10th September

Henlow.—Presidential Address. Professor A. J. Murphy. Building 62, R.A.F. Technical College, Henlow. 7.30 p.m.

19th September

Coventry.—Wind Tunnel Testing. G. Beech. Wine Lodge, The Burges, Coventry. 7.30 p.m.

24th September

Henlow.—Aero-engines in Retrospect from 1915 to 1944. Major G. P. Bulman, C.B.E. Building 62, R.A.F. Technical College, Henlow. 7.30 p.m.

26th September

Luton.—Under-Water Television. G. G. Macneice. Town Hall, Luton. 7 p.m.

1st October

Derby.—MAIN LECTURE. First Sir Henry Royce Memorial Lecture—Sir Henry Royce, Bart. H. I. F. Evernden, M.B.E., Rolls-Royce Welfare Hall, Derby. 6.15 p.m.

10th October

Luton.—The A.R.A. Transonic Tunnels. A. B. Haines. Luton Public Library. 7 p.m.

11th October

Henlow.—MAIN LECTURE: Rocket Motors. S. Allen. Building 62, R.A.F. Technical College, Henlow. 8 p.m.

13th October

Luton.—Visit to Aircraft Research Association, Bedford.

17th October

Coventry.—Problems Associated with Production and Use of Wrought Aluminium Alloys. G. Forrest and K. Gunn. Wine Lodge, The Burges, Coventry. 7.30 p.m.

22nd October

Glasgow.—Development of the Jet Propulsion Gas Turbine. G. C. R. Mathieson. Royal Technical College, Glasgow. 7.15 p.m.

NOTE: ***Branch Hon. Secretaries are reminded that meetings for the October Diary must be received by 15th September.***

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

David William Allen (*from Graduate*)
Hedley Vandelow Allen (*from Graduate*)
Reginald Gene Austin (*from Graduate*)
Rowland John Barnard (*from Graduate*)
Harold Charles Beasley (*from Graduate*)
Cecil Harcourt Burge
Walter Cawood
William Alfred Caws (*from Graduate*)
John Charles Chicken (*from Graduate*)
Raymond John Close (*from Graduate*)
Noel Parker Coupe
Howard Reuben Wallace Deacon
Thomas Edwards
Willie Farrar (*from Graduate*)
David Jeremy Fermo (*from Graduate*)
Arthur Sydney Forster (*from Graduate*)
George Edward Fowler (*from Graduate*)
Henry Robert Free
Owen Desmond Arthur Charles Furlong (*from Associate*)
Norman Keith Ayliffe Gardner (*from Associate*)
Howard Faraday Leonard Tyson Harrison
James Rentoul Henry (*from Graduate*)
Norman William Hodgson
James Thomas Dennis Holt
George Robert Kenneth Jameson
Peter Jefferson (*from Graduate*)
Ernest Theodore Labett (*from Graduate*)
Geordie Keith Larney (*from Associate*)
Roy Lindop
Derek Malcolm Holmes Lowe
Charles Alan Mitton (*from Graduate*)
Kenneth John Mundy
David Albert Needs (*from Graduate*)
Eric Newton (*from Associate*)
Albert George Payne (*from Associate*)
Vassilios Petsounis
Harry Percy Punter
Paul Leon Albert Raes (*from Graduate*)
Horace Sinclair Rainbow (*from Companion*)
Tecwyn Roberts (*from Graduate*)
John Dumella Rose
Josef Rosenthal (*from Graduate*)
Michael William Salisbury (*from Graduate*)
John Anthony Scott (*from Graduate*)
Harold George Sevier (*from Graduate*)
Derrick Francis Simpson (*from Graduate*)
Elias Charles Walter Stephen Smith
Frederick Arthur Summerlin
Reginald David Swift (*from Graduate*)
Richard Edgar Thomas (*from Graduate*)
Robert Henry Thring
Stanley Montague Maurice Turner
John Williams
Laurence Anthony Willott
Kenneth Frederick Wood (*from Graduate*)
David Robert Wright

Associates

George Arthur Haddon Cooper
Alwyn Wootton Crowther
Gordon Reginald France
Leslie Anderson Freeguard
Roy Charles Godwin
Kenneth Charles Edwin Jackson
Robert John Bazley Jackson
Alexander Vivian Leake (*from Student*)
Mervyn Joseph O'Brien
Charles Edward Frederick Page
George Guthrie Petrie Thorburn (*from Companion*)
Arthur Robert James Thorogood
Stanley John Turner
Leo Thomas Watson
Arthur Malcolm Weston West
Robert Edwin Wilkins
Francis George Wilson

Graduates

Keith Eric Allen
Beryl Edna Beadle (*from Student*)
Eugene Forrest Dearing
Dennis Peter du Plooy
Norman Michael Fox Heaton
Keith Ralph Hodge (*from Student*)
Peter Byan Ivanoff
Richard Penderell Llewelyn (*from Student*)
Edward Parker
Thomas Peter Rome
Ian Traill Sutherland (*from Student*)
Michael Leyland Woodward (*from Student*)

Students

Michael John Champniss
Robert Chapman
John Duerden
James Edmund Fairhurst
John Hensley Goodey
John Michael Hold
Stewart Irving
John Calvin Jones
N. Sampath Kumar
Brian Harold Long
Robert Vernon Percival
Peter Richard Schneidau
Anthony Colin Smith
Guy Rudgard Webster
David John Wheeler
Donald Lyall Wilson
Robert Richard Wilson

Companions

Doris Dockrall Hughes
David Surrey Littlemore
Eric Arthur Perry

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 60 SEPTEMBER 1956 NUMBER 549

The High Temperature Turbo-Jet Engine

by

D. G. AINLEY, B.Sc., A.M.I.Mech.E., A.F.R.Ae.S.

(National Gas Turbine Establishment)

The 985th Lecture to be given before the Society, "The High Temperature Turbo-Jet Engine" by D. G. Ainley, B.Sc., A.M.I.Mech.E., A.F.R.Ae.S., was given at the Institution of Civil Engineers, Great George St., London, S.W.1 on 15th March 1956, with Mr. N. E. Rowe, C.B.E., D.I.C., F.C.G.I., F.I.A.S., F.R.Ae.S., in the Chair. Introducing the Lecturer, Mr. Rowe said that Mr. Ainley had been working on gas turbines since 1943 when he joined the gas turbine division of the Royal Aircraft Establishment. He transferred to Power Jets Ltd. and later to the National Gas Turbine Establishment. His early work was associated with the development of axial flow compressors, contraction design and so on; he then transferred to turbine design, became head of the section dealing with turbine and heat transfer problems and for the past five or six years had been chiefly engaged on the cooling of gas turbine blades. Mr. Ainley graduated from the University of London, Queen Mary College, with first class honours. In 1953 he was awarded the George Stephenson Research Prize by the Institution of Mechanical Engineers.

1. Introduction

Throughout the history of powered flight the demand of the aircraft designer has been, and apparently always will be, for more "push" and, in the same breath, less weight and bulk of the power unit and its fuel supply. It is to appease further this insatiable demand for ever higher thrust/weight ratios that the development of the high temperature turbo-jet engine is directed.

Indeed, for the speeds of coming generations of aircraft to be pushed well beyond the threshold of Mach one it becomes essential to raise jet-engine gas temperatures substantially above current levels if useful flight ranges and endurances are to be achieved. Also, for subsonic flight, it is well recognised that the turbo-prop engine may benefit materially by similar rises in gas temperature.

However, raising gas temperatures without seriously reducing engine life and reliability is no mean task. Since Sir Frank Whittle's W.I.A. engine first propelled the Gloster E.28 aircraft in 1941, engine gas temperatures have risen little more than 100°C, although as a result of improved techniques of light construction and the development of the axial flow compressor the thrust to weight ratios of jet engines have increased roughly threefold and thrusts per unit frontal area have increased roughly tenfold.

Although some further improvements in light construction might be expected they must inevitably be of diminishing magnitude. In fact, the time is clearly upon us when the problems of high temperature operation have to be faced squarely if substantial future progress is to be made.

This calls for new technological advances, and during past years a great deal of preliminary study and research has been pursued to clear much of what would seem the roughest ground ahead of engine development. This preliminary work forms the main theme to the present lecture.

The intention of this lecture is to discuss in broad terms the major problems of high temperature operation. These centre primarily about the highly stressed turbine blades which are wholly submerged in the very hot gas stream. It is inevitable, therefore, that the paper must be chiefly pre-occupied with the turbine blade problem and with the possible solutions within grasp. From this it is possible to make some prediction, admittedly hazy, of the levels of gas temperature that might be attained in the foreseeable future in turbo-jet engines for supersonic flight.

First, however, it is worth glancing briefly at some of the aircraft applications for which the high temperature engine is suited.

2. The Incentive for High Gas Temperatures

2.1. LONG RANGE HIGH SPEED AIRCRAFT

For very long flight ranges the fuel load outweighs the engine weights and a low specific fuel consumption is of paramount importance. Fig. 1 is a familiar type of diagram illustrating the interdependence of specific thrust and fuel consumption with the engine maximum cycle temperature and compressor temperature rise, at flight speeds of $M=0.75$ and $M=2.5$ in the stratosphere. Figure 2 illustrates the trend of increasing gas temperature required to achieve minimum possible specific fuel consumption with increasing flight speed. If temperatures a little in excess of those required for minimum consumption are employed, the specific fuel consumption rises only slightly but the specific thrust will increase appreciably (Fig. 1), resulting in a reduction in engine weight, frontal area and nacelle drag. The optimum gas temperature for a minimum total value of engine and fuel weight over a prescribed

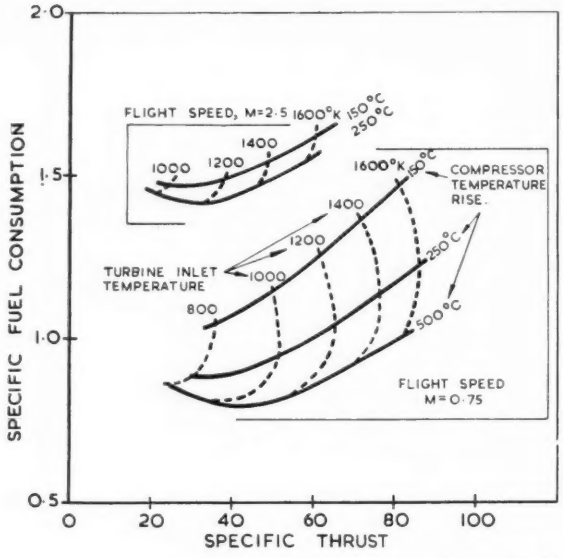

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FIGURE 1. Turbo-jet engine performance.

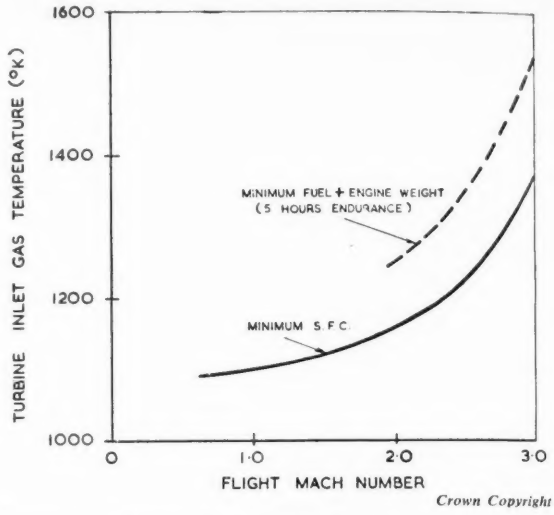

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FIGURE 2. Variation of optimum gas temperature with flight speed.

flight range and speed will, in practice, be higher than the temperatures shown in Fig. 2—only slightly higher for very long range but becoming increasingly greater as range is reduced. This is indicated by the broken line in Fig. 2 which illustrates the approximate optimum cycle temperature for minimum total weight of engine and fuel if an endurance of 5 hours at 60,000 ft. were stipulated. For an endurance of 3 hours the curve rises roughly by a further 100°C. For long range supersonic aircraft travelling at a Mach number of 2 to 2.5 it would seem therefore that the optimum gas temperatures lie roughly in the region of 1,250 to 1,450°K, these temperatures being 100 to 300°C higher than present-day values in uncooled engines.

2.2. SHORT RANGE INTERCEPTOR AIRCRAFT

For this type of aircraft the assessment of optimum engine temperature is vastly more difficult, depending very much on the operational role that is specified for the aircraft. To a limited degree it might be said that on some aircraft of this type the advantage of high gas temperature, so far as thrust power alone is concerned, is already being reaped as a result of the development of reheat. Use of reheat, however, imposes very high rates of fuel consumption and invariably it would be more efficient to operate with high gas temperatures in the main engine combustion chamber than to pour fuel into a jet pipe after-burner. Figure 3 compares the 1-*g* ceiling performance of a hypothetical supersonic aircraft propelled respectively by low and high temperature engines, both with and without reheat, the engines in all instances having a bare weight equal to 20 per cent. of the aircraft all-up weight. This indicates that high turbine inlet temperatures may have only a small beneficial effect on maximum height and speed when a high degree of reheat is employed. On the other hand, the unreheated high temperature engine is vastly superior to the unreheated low temperature engine and, furthermore, provides a flight performance approaching that attainable with reheat but with fuel consumption more than 25 per cent lower.

A picture of this type is of course an over-simplification. Other considerations such as rate of climb, acceleration, manoeuvrability, must enter and complicate the problem.[1] Indeed, the optimum form of power plant, or combination of power plants, remains a subject for speculation. Nevertheless, it seems clear that an ability to operate jet engines at, say, 1,500 to 1,600°K might ease, even though it might not solve, this question.

2.3. TURBO-PROP AND BY-PASS ENGINES

In this field there is everything to gain by raising gas temperatures. With a proper adjustment of engine pressure ratio both thrust to weight ratio and fuel consumption might be improved. For example, in a turbo-prop engine installed in an aircraft flying at 400 knots in the stratosphere an increase in gas temperature from 1,100°K to 1,400°K could lead to an increase in specific power output or roughly 50 per cent, combined with a reduction in specific fuel consumption of about 10 per cent. Clearly, such an improvement cannot be overlooked and it might be anticipated that the development of the high temperature turbo-jet engine will pave the way for similar developments in the turbo-prop field.

3. Problems

The biggest single problem that impedes the development of the high temperature engine is presented by the highly stressed blades in the turbine component. Two possibilities always lie open. New material for the blades might be sought, capable of operating at appreciably higher temperatures than those currently used. Failing this, then a means of cooling blades made

of current materials must be found which will allow the gas temperatures to be raised while the actual blade materials are maintained at broadly the same temperatures as those at which they operate in present uncooled engines. The provision of such cooling means would also enable engines to operate at current levels of gas temperature with blades made of much lower quality materials. Such an application is unlikely to reduce cost, however, and only arises importantly if higher grade materials are simply not available (as was the case in Germany during the 1939-45 War).

Problems, mainly of cooling, also centre around the combustion chamber, jet pipe and propelling nozzle. High combustion outlet temperatures necessitate improved methods for cooling combustion chamber linings and jet pipe surfaces. Higher combustion intensities and improved mixing of primary and secondary air may also be required if the combustion chamber volumes and lengths are not to increase substantially, or if turbine inlet gas temperature traverses are not to become undesirably non-uniform.

The high temperature engine being particularly suited to supersonic flight, the high gas temperature problems will be accompanied by those associated with the design and performance of supersonic air intakes and with high entry air stagnation temperatures.

The combustion chamber, jet pipe, and nozzle problems are essentially extensions of those already existing. Although they are far from trivial they appear unlikely to prove critical. The present paper is therefore confined primarily to the problem which has until now dominated the high temperature engine, namely that of the turbine blading.

4. Development of New Blade Materials

The improvement of nickel or cobalt base heat and creep resistant metallic alloys is slowly approaching an ultimate limit of development. Taking even an optimistic view it is improbable that further developments in these materials will lead to increases in permissible blade temperatures greater than about 50 to 100°C. Use of molybdenum alloys may yield a further improvement.[33] Molybdenum, however, oxidises rapidly at high temperatures and its use as a blade material is dependent upon the development of a reliable protective surface coating. For uncooled operation at high temperatures the potentialities of a wide range of ceramic materials, or mixtures of metals and ceramics (christened variously as cermets, ceramels, or metamics) are currently being explored. Although there has always been a certain amount of hope associated with these materials there has, as yet, been little sign of fulfilment. Several ceramics have attractive creep and oxidation resistance properties in the 1,200 to 1,400°K region and are relatively cheap and readily available. In general, however, they possess the common feature of brittleness to a high or moderate degree and in consequence are prone to breakage by mechanical, or possibly, thermal shock. This constitutes a serious barrier to their use as turbine blade materials, particularly in aircraft engines where an ability to withstand frequent and rapid

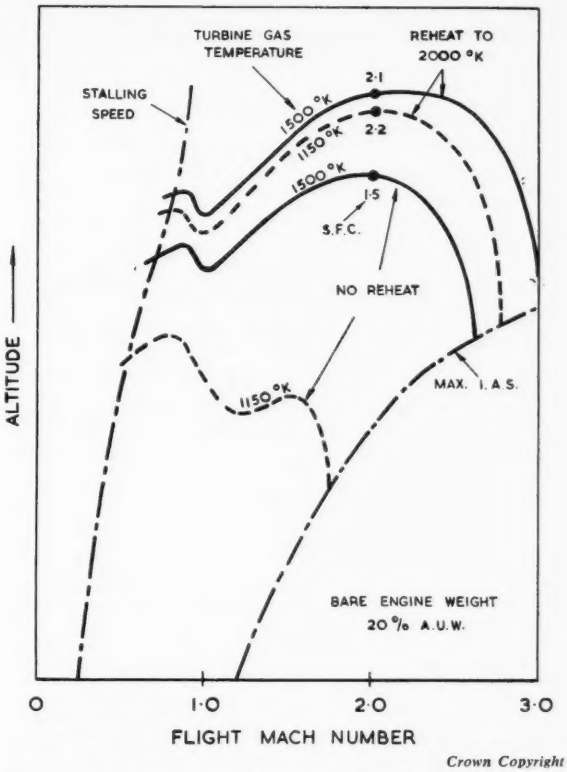

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FIGURE 3. 1-*g* ceiling performance of hypothetical supersonic fighter aircraft.

changes in engine operating conditions is mandatory. Fig. 4 summarises simply the pros and cons of ceramic materials! Mixing with a metal such as nickel, cobalt, or chromium tends to improve ductility, and hence resistance to shock, but simultaneously reduces the high temperature creep and oxidation resistance. Although a few recently developed materials show a little promise (such as silicon carbide, chromium/alumina, nickel or cobalt bonded titanium carbide, etc.)[34-37] it is improbable that materials of this type will find application for other than stationary blades in the foreseeable future, and in rare instances only. Nevertheless there is a relatively new and expanding technology in the ceramic and cermet field and hope, at least, still remains. In the meantime lack of fulfilment drives us to the alternative of blade cooling. Incidentally, any future developments of improved high temperature materials are unlikely to displace blade cooling, but rather may enhance its potentialities since, with cooled blades, a rise of, say, 50°C in permissible blade temperature would allow a substantially greater increase in gas temperature.

BLADE COOLING

5. Outline of the Problem

If turbine blades are cooled to temperatures well below that of the gas, then heat will be transferred to the blades at a high rate and this heat must be

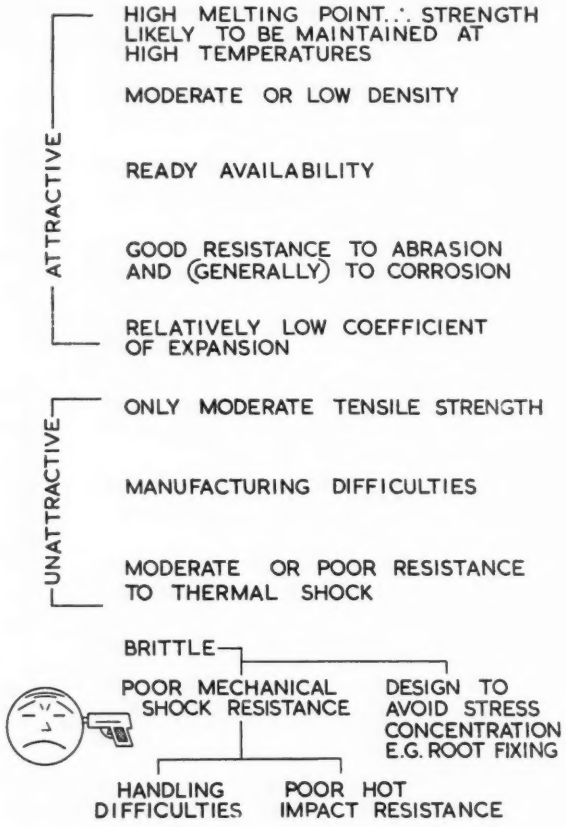
ATTRACTIVE
HIGH MELTING POINT.·. STRENGTH LIKELY TO BE MAINTAINED AT HIGH TEMPERATURES
MODERATE OR LOW DENSITY
READY AVAILABILITY
GOOD RESISTANCE TO ABRASION AND (GENERALLY) TO CORROSION
RELATIVELY LOW COEFFICIENT OF EXPANSION
UNATTRACTIVE
ONLY MODERATE TENSILE STRENGTH
MANUFACTURING DIFFICULTIES
MODERATE OR POOR RESISTANCE TO THERMAL SHOCK
BRITTLE
POOR MECHANICAL SHOCK RESISTANCE
DESIGN TO AVOID STRESS CONCENTRATION E.G. ROOT FIXING
HANDLING DIFFICULTIES
POOR HOT IMPACT RESISTANCE

FIGURE 4. Ceramics: general characteristics.

continuously removed by a coolant. The extraction of heat from the gas as it passes over the cooled blades reduces the gas temperature in later stages of the turbine and in the propelling nozzle and thus causes a reduction in overall engine performance from that ideally attainable. A further loss in power results from the energy required to pump the coolant to the blades. Finally, the introduction of a cooling system may tend to increase the weight and mechanical complexity of the engine and also the drag of the engine components in an aircraft installation. These factors must be taken into account when assessing the potentialities of a cooled high temperature engine.

In the following sections the rates of heat transfer between a gas stream and blades are discussed first. These rates of heat transfer are inescapable and tend to dominate the resulting characteristics of any cooling system. The efficacy of various cooling systems for removing these quantities of heat are then considered. Finally, an indication is given of the gas temperatures that might be achieved eventually with a preferred type of turbo-jet blade cooling system, and also the manner in which these gas temperatures may be influenced by the flight speed and altitude of the aircraft in which the engines are installed.

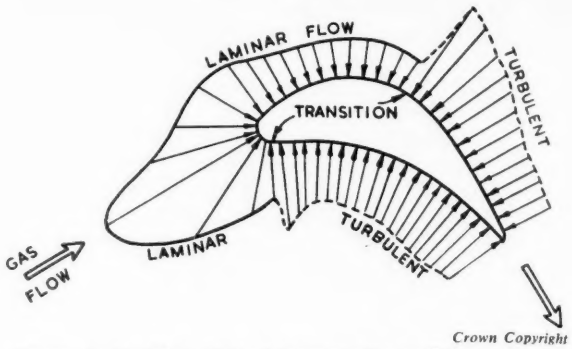

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FIGURE 5. Variation of local heat transfer coefficient around a typical turbine blade section.

6. The Gas to Blade Heat Transfer Process

When a blade is maintained at a lower temperature than the effective gas temperature* heat is transferred to the blade mainly by forced convection. Heat may also be conducted or radiated to or from the blade, but in a cooled turbine these heat flow rates will usually be small compared with the forced convection heat transfer.

Figure 5 illustrates the manner in which heat transfer coefficients vary locally around a typical turbine blade profile[4, 5]. High local rates of heat transfer occur at the leading edge where the boundary layer is thin and laminar. The values decrease as the boundary layer builds up around the surface and then increase sharply when the boundary layer becomes turbulent.

Figure 6 illustrates the manner in which the average heat transfer coefficient† for the whole blade surface varies with Reynolds number (Re), blade shape, and the position of the points of transition in the boundary layer[6]. On blades of different shapes the average heat transfer rates are roughly the same if the transition points happen to occur at the same relative positions on the blade surface. In practice, blade shape will largely govern the position of the points of transition. Thus, on a high reaction blade (*e.g.* nozzle blade) the pressure gradients are favourable over a large proportion of the blade surface and a relatively large area of laminar flow may occur with correspondingly low rates of heat transfer. On low reaction blades the pressure gradients are less favourable and a greater extent of turbulent

*The temperature that an uncooled body would attain in the same gas stream, there being no conduction or radiation of heat to or from the body.

†It is convenient to express heat transfer coefficients non-dimensionally in the form of a Nusselt number, Nu. In standard text books[2, 3] it is demonstrated that Nu is primarily a function of Reynolds number (Re), Prandtl number (Pr), and blade shape. Fortunately, with air Pr remains substantially constant under all conditions of temperature and pressure appropriate to gas turbine applications.

$$\text{Heat transfer coefficient} = \text{heat quantity transferred per second per unit surface area per degree temperature difference between gas and surface.}$$

$$\text{Nusselt number} = \frac{\text{heat transfer coefficient} \times \text{blade chord}}{\text{thermal conductivity of gas stream}}$$

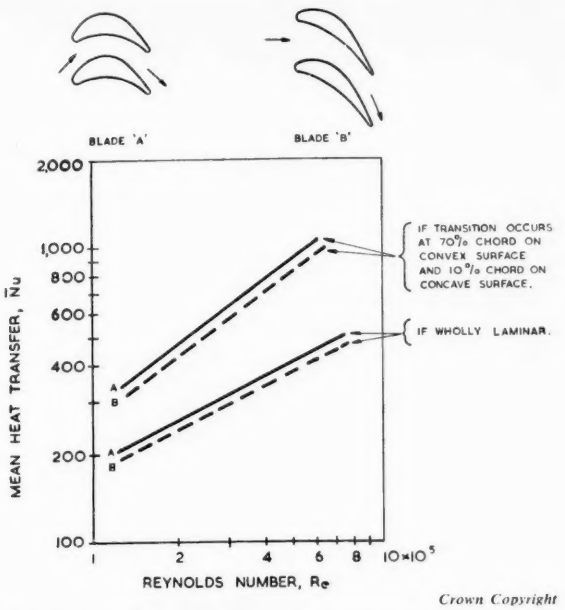

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FIGURE 6. Influence of Reynolds number, blade shape and position of transition points upon the mean rate of heat transfer to turbine blades (theoretical).

boundary layer will exist, with correspondingly higher rates of heat transfer.

This is illustrated in Fig. 7, which demonstrates that there is a rough correlation between mean heat transfer coefficient and the blade reaction as expressed by the ratio of inlet blade angle to outlet gas angle. The lower curve for blades in stationary cascades is derived from experimental data drawn from a wide variety of sources[7, 8, 9, 10, 11]—different tunnels, different degrees of main stream turbulence, unrelated blade shapes, and different test techniques. It seems significant that, in spite of this, such a simple correlation gives a general scatter of less than about ± 20 per cent.

The mean Nusselt number generally varies with Reynolds number approximately in proportion to Re^x, where x varies between 0.5 (for a wholly laminar flow) and 0.8 (for a wholly turbulent flow). The scatter in experimental values is fairly large and probably arises as a result of small movements of the transition points with Re over the experimental test ranges. In practice the value of x is important since, as will be indicated later, its value largely governs the influence that altitude and engine size may be expected to have on the cooling characteristics of the blades in a turbo-jet engine.

Nearly all existing data for heat transfer to turbine blades have been obtained from experiments on stationary cascade tunnels. No very accurate experimental data exists for heat transfer rates to blades within an actual turbine stage, where gas flows are more turbulent and unsteady than in a cascade tunnel. It may be anticipated that this will lead to earlier transition and higher rates of heat transfer in the actual turbine stage. Approximate estimates have been made from data extracted from an experimental turbine operated at N.G.T.E.[12] and from these the dotted lines in Fig. 7 have been speculatively introduced.

The values shown of non-dimensional Nusselt number give little hint of the actual physical heat quantities involved in cooling a turbine blade row. On typical engines the rates of heat transfer range from about 0.02 to 0.2 C.H.U. per sq. ft. per sec. per °C, these values corresponding roughly to a small engine at high altitude and a large engine at low altitude, respectively. On an average size engine, swallowing 150 lb. of air per sec. at sea level, the surface area in one row of turbine blades may be roughly about 3 sq. ft. If such an engine were flying at a Mach number of 2 at 60,000 ft. and an average temperature difference of 350°C were maintained between the blades and the gas stream, then the heat which must be removed from one row of turbine blades would be roughly equivalent to that required to boil away 200 lb. of water per hour. For a two-stage turbine this might amount to roughly 25 per cent of the fuel flow rate, by weight, and the heat absorbed would be more than that required to vaporise the total fuel flow. For those interested in the problems of cooling the structure of a supersonic aircraft the following comparison may be of academic interest. In the engines operating at 1,500°K in the hypothetical

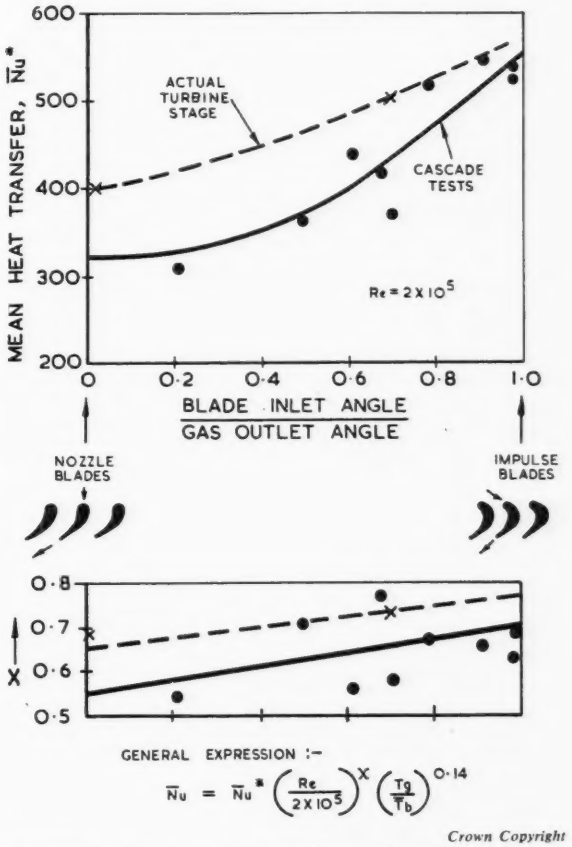

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FIGURE 7. Correlation of experimental data for mean heat transfer rates to turbine blades.

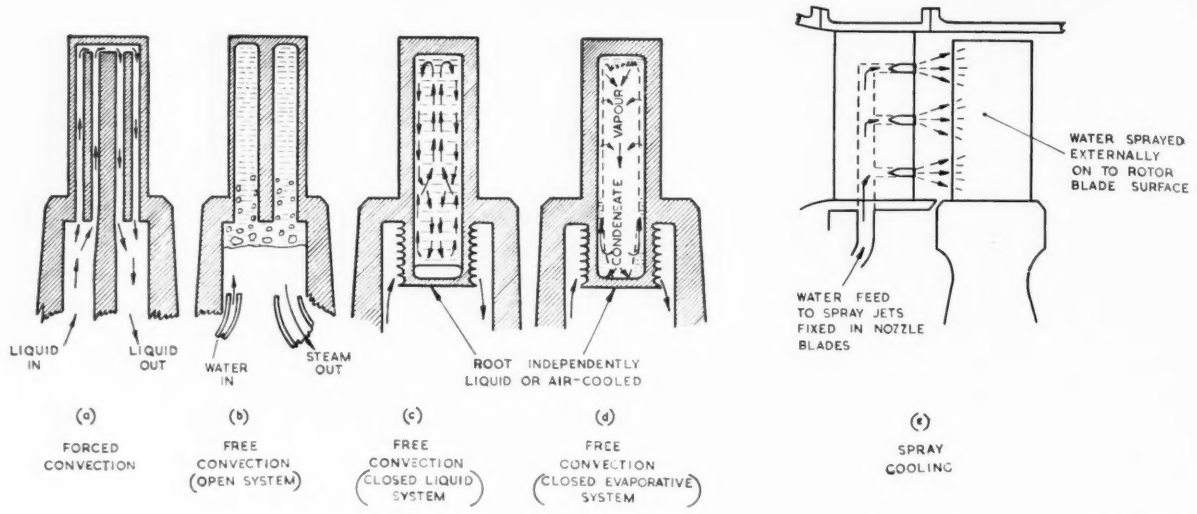

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FIGURE 8. Schematic illustration of various liquid cooling methods for turbine rotor blades.

supersonic fighter mentioned in Section 2.2, the quantity of heat to be extracted from the turbine blades is equivalent to the quantity of heat that would have to be extracted from the aircraft to cool the entire external aircraft surface by an amount of the order of 100°C when flying at a Mach number of 2.5.

7. Methods of Blade Cooling

The number of methods that have been proposed throughout the world for extracting those quantities of heat are legion. Indeed, the existence of this problem must have created a lucrative source of revenue to the Patent Office! Within the confines of this one paper it would be impossible to give an exhaustive account of these many ideas and the reasons for rejecting a large proportion of them. A few general comments leading to the type of scheme favoured at present must suffice.

Broadly speaking the methods proposed fall into three groups:—

(*i*) Pure liquid-cooling schemes. In such schemes the heat is absorbed by an expendable quantity of liquid, such as water or the engine fuel (probably vaporising in the process), and no attempt is made to re-cool or condense the liquid for repeated use as a coolant.

(*ii*) Combined liquid/air cooling schemes. As with the first group the heat is removed from the blading by a liquid coolant, but the heated liquid (or vapour) is then circulated and cooled (or condensed) in either a ram-air radiator or an air-heat exchanger situated in the engine itself between the compressor and combustion chamber.

(*iii*) Pure air-cooling schemes, in which cool air is passed directly through the inside of the turbine blades.

7.1. LIQUID AND LIQUID/AIR COOLING METHODS

Consider briefly the pros and cons of the liquid cooling methods. In the first place it must be said that, in general, liquid coolants are quite satisfactory for removing the necessary quantities of heat from the blades themselves. This has been demonstrated both by laboratory tests and by tests on actual experimental turbines in Germany, the United States and Great Britain[17, 24, 29-32]. A particularly striking demonstration[38] was the operation by N.A.C.A. at gas temperatures up to 1,100°C of a water-cooled turbine constructed entirely of aluminium—although this was, perhaps, more of academic than of practical interest. The various methods which have been most actively considered for blade cooling with liquids are summarised schematically in Fig. 8. Those schemes involving free convective cooling rely on the very high gravitational field in rotor blades (of the order of 20,000 *g*) which causes the lighter heated fluid or vapour to move rapidly, radially inwards to the blade root—and are only applicable to rotor blade cooling. For further details on these schemes the reader is referred to the published literature in the references.

With liquid cooling it has already been demonstrated[24, 38] in the laboratories that gas temperatures in the region of 1,400-1,500°K may be achieved and there is no reason to suppose that even higher gas temperatures would not be possible. The reduction of engine performance arising from the cooling losses (*i.e.* extraction of heat from the blades and power required for pumping the coolant to the blades) may be small, so far as thrust and fuel consumption in turbo-jet engines are concerned. Features which are less attractive, however, are the mechanical complications to the engine which are associated with liquid cooling, and also the additional weight and drag of the coolant and coolant system which detracts from the combined performance of an engine and aircraft.

Systems employing an expendable quantity of water (such as spray cooling) are the least complicated mechanically, but it has already been indicated that a weight of water amounting to 20 per cent or more of the fuel weight would have to be carried in the aircraft for continuous engine operation at a gas temperature of 1,400-1,500°K, and such a penalty detracts seriously in all but the very special application where high gas temperatures and cooling are used only for a very brief flight duration. If the engine fuel is used as the coolant the weight penalty disappears and is replaced by new complications in the form of difficulties and hazards in circulating fuel or fuel vapour into and out of a high speed rotor, the danger of cracking the fuel, and possible complications to control in the engine and combustion system. Furthermore, the low specific and latent heats of hydrocarbon fuels limit the degree of cooling achievable to a value little or no better than may be achieved by other simpler methods to be described shortly.

The liquid/air systems are, in theory, more attractive, particularly for long flight endurance. Weight penalties and mechanical complexities appear, however, in the form of radiators or heat exchangers and the provision of glands, etc., for circulating a liquid into and out of a high speed rotor without leakage. A small leakage might not be serious if water were used as the coolant, but the low critical temperature of water (critical temperature 374°C; critical pressure 3,200 p.s.i.) restricts its use in such systems to flight speeds less than about a Mach number of 1.5. At appreciably higher flight speeds the high stagnation temperature of the ram-air which must be used for cooling the liquid may necessitate the use of a liquid metal such as sodium or sodium/potassium eutectic and this imposes very difficult mechanical problems.

7.2. AIR-COOLING METHODS

If we turn now to the alternative of pure air-cooling, most of these mechanical complexities and other complications virtually disappear (Fig. 9). In fact, it is the relative simplicity of air-cooling that has led to its

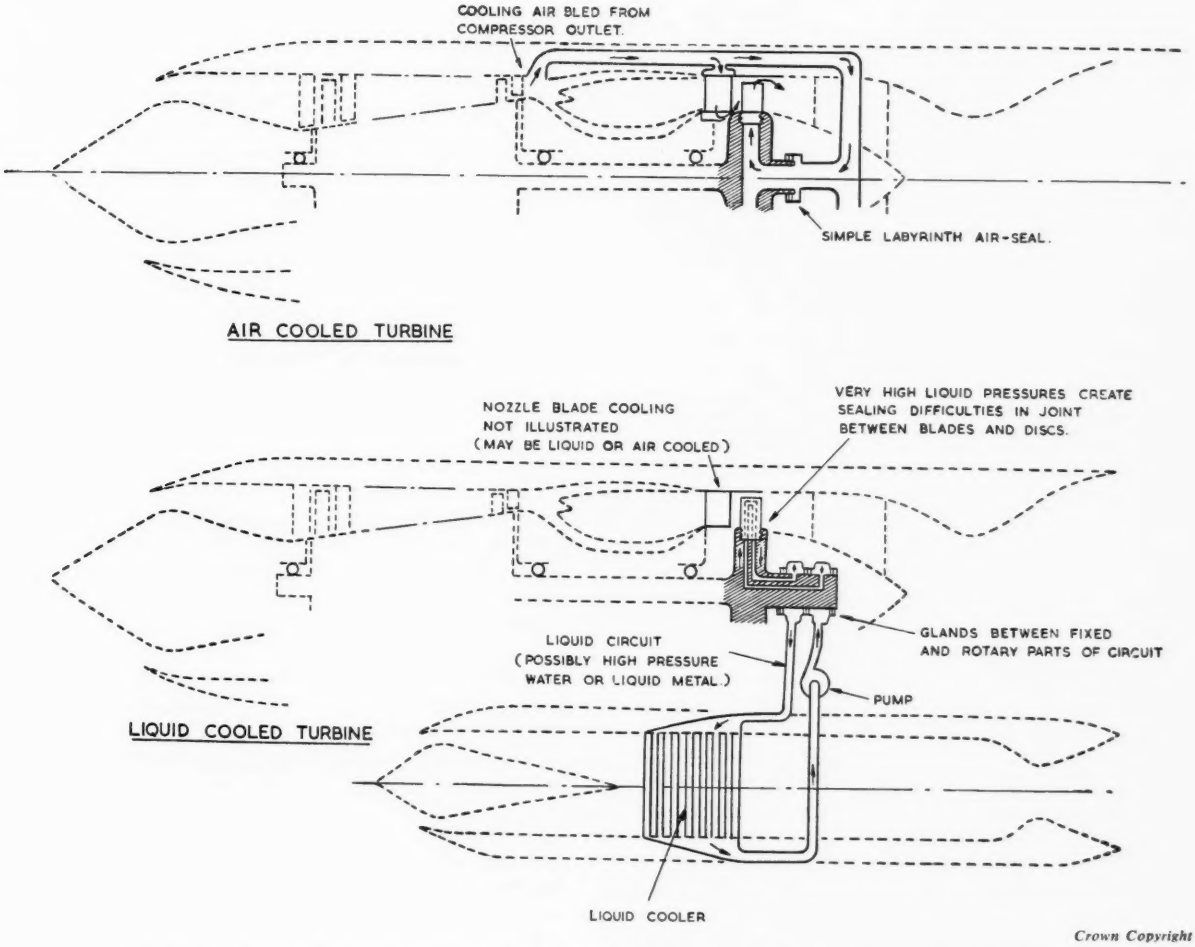
COOLING AIR BLED FROM COMPRESSOR OUTLET.
SIMPLE LABYRINTH AIR-SEAL.
AIR COOLED TURBINE
NOZZLE BLADE COOLING NOT ILLUSTRATED (MAY BE LIQUID OR AIR COOLED)
VERY HIGH LIQUID PRESSURES CREATE SEALING DIFFICULTIES IN JOINT BETWEEN BLADES AND DISCS.
GLANDS BETWEEN FIXED AND ROTARY PARTS OF CIRCUIT
LIQUID CIRCUIT (POSSIBLY HIGH PRESSURE WATER OR LIQUID METAL)
PUMP
LIQUID COOLED TURBINE
LIQUID COOLER

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FIGURE 9. Schematic illustration comparing turbo-jet engines with air-cooled and liquid-cooled turbine blades.

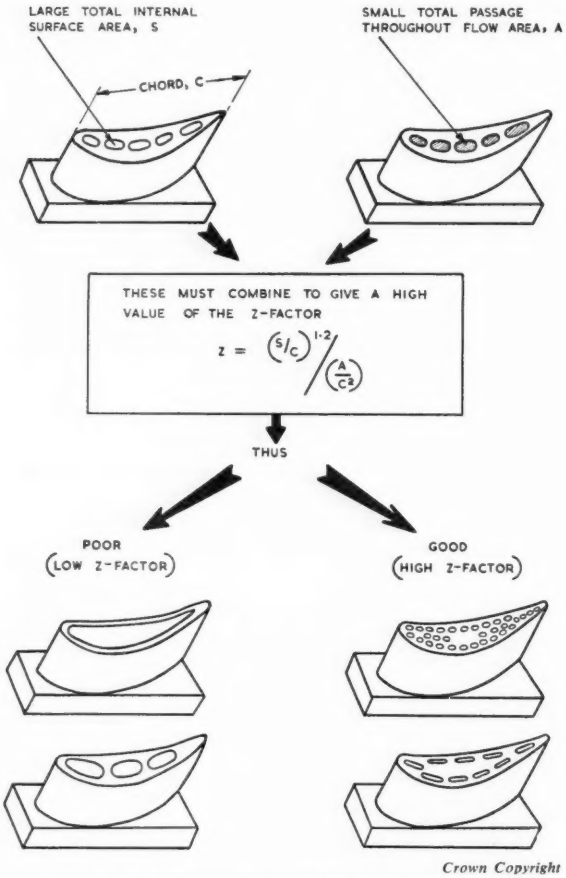
LARGE TOTAL INTERNAL SURFACE AREA, S
SMALL TOTAL PASSAGE THROUGHOUT FLOW AREA, A
CHORD, C
THESE MUST COMBINE TO GIVE A HIGH VALUE OF THE Z-FACTOR
$z = \left(\frac{s}{c}\right)^{1\cdot2} \Big/ \left(\frac{A}{c^2}\right)$
THUS
POOR (LOW Z-FACTOR)
GOOD (HIGH Z-FACTOR)

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FIGURE 10. Requirements for efficient internal air-cooling.

S = internal surface area of cooling passages per unit blade height.

A = cross-sectional flow area of cooling passages.

c = blade chord.

being the most favoured system at present for aero-engine application—particularly in those applications appertaining to supersonic flight.

In the preferred type of air-cooling systems the cooling air is bled from the high pressure end of the main engine compressor and passed through internal cooling passages within the turbine blades and finally discharged from the blades back into the main gas stream. Now, in a turbo-jet engine designed for, say, a flight speed of $M = 2$ the temperature of the cooling air bled from the compressor may be in the region of 350-450°C, while the average turbine blade temperature will be required to be about 750-850°C. There is thus a difference in temperature between the blades and the incoming cooling air of about 400°C. If the internal heat exchange system between the blades and cooling air was so perfect that the cooling air was discharged from the blades at a temperature equal to the mean blade temperature, then in theory it would be possible to maintain a temperature difference of about 300°C between the gas stream and the blades in one row of turbine blades with a quantity of cooling air of the order of one per cent of the total engine air mass flow.

As will be indicated later, it is difficult to achieve so perfect a heat exchange system within a blade and in practice the quantities of cooling air may need to be in the vicinity of 1½ per cent to 2 per cent per row of turbine blades. Thus, with a two-stage turbine (four rows of blades) a turbine inlet gas temperature of about 1,400-1,500°K may be feasible at the expense of about 6 to 8 per cent of the compressor air-flow for cooling. To pass these necessary quantities of cooling air through the small internal volume of the turbine blades, simultaneously achieving a high internal rate of heat transfer, unfortunately requires that the cooling air be at a high pressure. Bleeding 6 to 8 per cent of the compressor air-flow from the high pressure end of the compressor naturally causes a reduction in overall engine performance from that which is ideally attainable. A compensating effect is introduced, however, in that the cooling air is returned to the main stream after doing its job of blade cooling, so that the full engine mass flow is still available for final expansion through the propelling nozzle, although at a slightly reduced temperature due to the dilution effect. The net result is that when these cooling losses are allowed for in a turbo-jet engine, about 80 per cent of the ideal gain in net engine thrust due to raising the gas temperature may, in fact, be achieved. Although small, the cooling losses are slightly greater than with the liquid cooling systems. On the other hand the weight or drag penalties and the mechanical complications are very much less than those associated with liquid cooling systems.

These factors lead to the conclusion that the overall performance of a high speed jet-propelled aircraft equipped with a relatively simple air-cooled engine differs but little from one fitted with a slightly more efficient, but bulkier and more complex liquid-cooled engine—at least up to "modest" gas temperatures of 1,400-1,500°K. Relative simplicity, therefore, is the major attraction of an air-cooling system and also, synonymous with simplicity, reliability.

This may not be quite so true for the high temperature turbo-prop engine flying at subsonic speeds.. In this instance a liquid/air cooling system may allow slightly lower rates of fuel consumption than with air-cooling and the penalties imposed by the provision of a ram-air radiator will be of lesser magnitude. Even so, the importance of simplicity and reliability will still weigh heavily in favour of air-cooling in such engines and, accepting that air-cooling is favoured for the turbo-jet engine, the valuable experience gained in the development of the air-cooled turbo-jet engine will provide a further bias toward the adoption of air-cooling for the high temperature turbo-prop.

The ultimate potentialities of air-cooling hinge upon the practicability with which turbine blades might be produced having suitably efficient internal cooling configurations when passing cooling air quantities of the order of one per cent to two per cent of the main gas flow. This subject is taken up in the following sections.

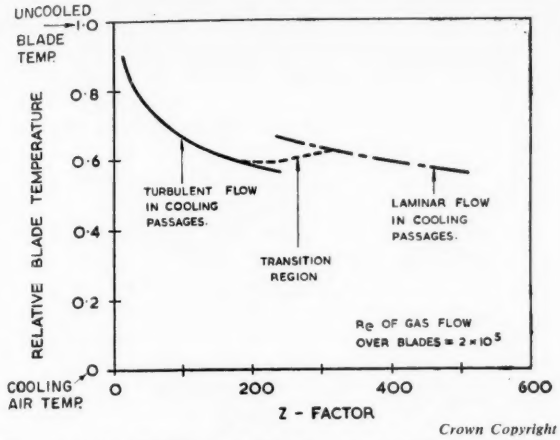

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FIGURE 11(*a*). Influence of *Z*-factor on cooling of a typical turbine nozzle row.

[Cooling flow = 1·5 per cent. of main engine gas flow; pitch/chord = 0·75; outlet gas angle = 60°.]

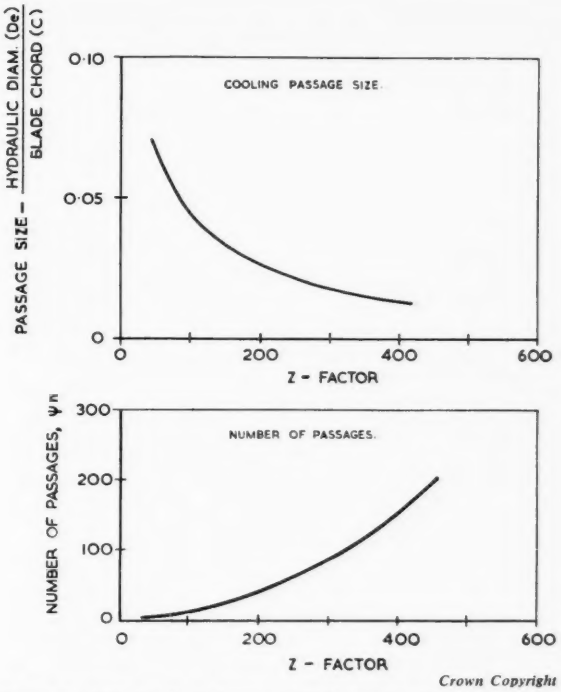
8. The Design of Air-Cooled Blades

8.1. EARLY GERMAN DEVELOPMENTS

It is well known that due to a scarcity of important alloying materials, such as nickel, during the 1939-45 War the Germans were the first to embark actively upon a programme for the development of cooled turbine blades for both turbo-jet engines and turbo-superchargers. Although they did some experimental work on both air and liquid cooling, all jet engines in production or development by the end of the war had air-cooled blades. This work has been amply recorded[13, 14, 15] and there is no cause to describe it afresh in detail here. The work was noteworthy chiefly on account of the considerable ingenuity exercised in producing large numbers of hollow sheet metal blades fabricated by deep drawing, pressing, and welding operations. They achieved only small degrees of cooling, very inefficiently from the thermodynamic point of view, the cooling being mainly confined to the region of the blade root. With turbine inlet gas temperatures of about 1,050°K it is recorded that the life of the turbine components rarely exceeded 50 hours. The reasons for the relatively poor cooling will be made evident in the ensuing paragraphs.

8.2. BASIC REQUIREMENTS FOR EFFICIENT INTERNAL AIR-COOLING

To achieve an efficient degree of cooling by passing a small fixed quantity of cooling air in a spanwise direction from blade root to tip through internal cooling passages, it is necessary to devise cooling passage shapes such that the internal cooled surface area is large. At the same time the cooling air must scrub the internal surfaces at a high velocity, which implies that the cross-sectional flow area of the passages must be small (Fig. 10). An analytical study[6] (which is too lengthy to be included here) shows that a useful figure of merit for comparing the relative efficiency of various cooling passage configurations within a blade of fixed external



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FIGURES 11(*b*), 11(*c*). Influence of *Z*-factor on size and number of cooling passages.

shape is a parameter, Z, equal to $(S/c)^{1\cdot2}/(A/c^2)$, which for brevity the author has termed the "*Z*-factor." For good cooling a high value of this *Z*-factor is required. The influence of Z on the average degree of cooling that might be achieved in a typical turbine nozzle blade row with a quantity of cooling air equal to 1.5 per cent (by weight) of the total gas mass flow is illustrated in Fig. 11(*a*). In this figure a standard practice is adopted of expressing the blade temperature on a relative scale such that the gas temperature (or, more correctly, the uncooled blade temperature) is unity and the inlet cooling air temperature (the lowest temperature which the blade could possibly attain) is zero. It will be observed that the degree of cooling increases rapidly with the *Z*-factor over a range of Z up to about 200. For values of Z greater than 200 the return becomes relatively small. Figs. 11(*b*) and 11(*c*) demonstrate that to achieve increasing values of Z, larger numbers of passages of diminishing size are required. The actual number of passages required to achieve any given value of Z depends very much upon the cross-sectional cooling passage shape. If the passages are of circular cross section the number of passages is a maximum. If passages of highly elliptical or rectangular cross section are used, the number of passages required is reduced and the cross-sectional area of each passage enlarged—possibly easing problems of manufacture.

It must also be stated that the degree of cooling can be greatly influenced by the aerodynamic design of the blade row (*i.e.* gas flow angles, pitch/chord, etc.) as well as by the quantity of cooling air used and the internal cooling passage arrangement. In theory the degree of

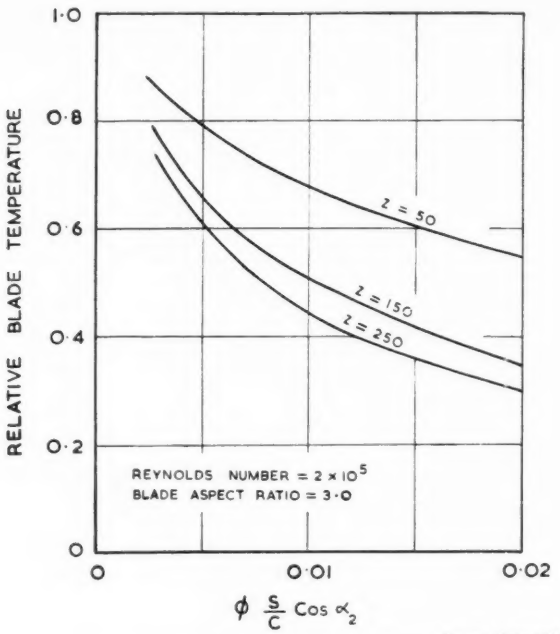

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FIGURE 11(*d*). General relationship between blade temperature, *Z*-factor and parameter (cooling flow ratio) × (pitch/chord) × (cosine of gas outlet angle).

ϕ = Cooling flow ratio
$\frac{s}{c}$ = $\frac{\text{Pitch}}{\text{Chord}}$
α_2 = Gas outlet angle (relative to axial direction)

cooling obtainable with a given cooling passage configuration (*i.e.* for a fixed value of *Z*) is a function, not of the cooling flow ratio alone, but of the product

(cooling flow ratio) × (pitch/chord) × (cosine of the gas outlet angle).

This is illustrated graphically in Fig. 11(*d*). Theoretically, the blade aspect ratio should also enter into this general relationship. In any study associated with a particular engine design, however, the choice of aspect ratio also influences the value of gas flow Reynolds number and the net effect of aspect ratio alone upon the average degree of cooling is small over a practical range of, say, one to four. In the view of the author it is, therefore, best omitted. It must be added, however, that the choice of aspect ratio will have a pronounced influence upon the frictional pressure losses occurring in the coolant flow, passing through the blades.

Thus it may be seen that to economise in cooling flow it is necessary to design blade rows with the widest possible pitch/chord ratio and low values of gas outlet angle. This is tantamount to saying that the external surface area of blading swept by the hot gas should be reduced as far as possible.

Unfortunately this may lead in practice to some loss in turbine expansion efficiency. The significance of this to the design of the turbo-jet engine is discussed later in Section 9.

The preceding remarks show that when the shapes and numbers of blades are suitably chosen the problem of obtaining a high degree of cooling in air-cooled blades of this type largely resolves itself into producing blades with internal passages having a high *Z*-factor. At the same time there are certain compromising factors which must be taken into account simultaneously and these are now listed:—

(1) There is a limit to the pressure drop that can be allowed in the cooling air as it passes through the blade. An upper limit is conveniently set by supposing that the cooling air is bled from the exit of the main engine compressor and that the cooling air is discharged from the turbine blade at the blade tips (*i.e.* the complication of a secondary "boost" compressor for the cooling air is not contemplated).

(2) Difficulties of manufacture of blades with large numbers of very small internal passages and dangers of blocking very fine passages with foreign particles in the air flow dictate against very high values of *Z*.

(3) Generally speaking it is desirable (although not

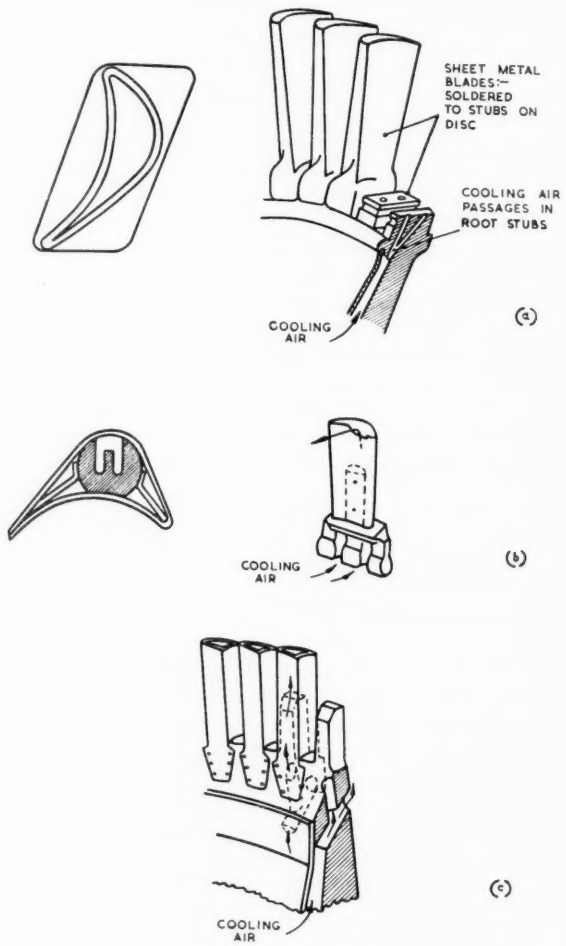

FIGURE 12. Early German blade cooling schemes (pre-1945).
(*a*) Jumo 004 jet engine.
(*b*) (*c*) D.V.L. supercharger schemes.

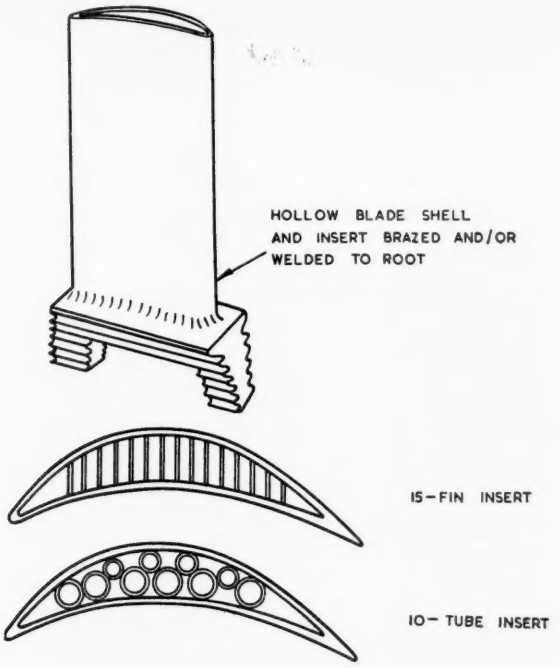

FIGURE 13. Illustration of two forms of air-cooled blade investigated by N.A.C.A. (Refs. 19 and 20).

essential) to retain turbulent flow in the cooling passages, and this sets a lower limit to the Reynolds number of the flow in the passages (and a corresponding upper limit to Z).

Of these compromising factors it is the problem of blade manufacture that has chiefly restricted the value of Z-factor, and hence the degree of cooling attainable up to the present time. Many new developments in methods of blade manufacture have arisen during recent years, however, and it might be hoped that manufacturing problems will cease to be the chief limitation in the foreseeable future. It is of interest to look briefly at some of the progress that has been made in this respect.

8.3. PRACTICAL DEVELOPMENT OF AIR-COOLED BLADES

Up to 1945 the Germans had confined themselves to plain hollow blades or blades with simple inserts (Fig. 12). Such blades gave only low Z-factors with the result that relatively poor cooling was achieved. The most promising blade was possibly that developed for supercharger application by the D.V.L. This consisted of a thin blade shell spot welded to a strong internal pillar of simple shape which acted as the main structural member, and cooling air was forced both through the spaces between the pillar and the blade shell and also through a channel in the pillar itself. This ensured that the main stress-carrying pillar was relatively well cooled. The leading and trailing edges of the shell, however, were relatively poorly cooled, although the main danger from this was one of buckling and oxidation of the shell, rather than of catastrophic failure. The effective Z-factor for this blade was about 50-60.

In the U.S.A. the N.A.C.A. have published results[16-23] on a variety of blades manufactured by brazing or welding together a number of component pieces. Diagrammatic sketches of some of these blades are shown in Fig. 13. Moderate values of Z-factor of about 100-120 were achieved by brazing fins or small diameter tubes into a hollow blade shell. The hollow shell was either cast or pressed from tube and then welded or brazed to the blade root. These blades, although exhibiting moderate or good cooling characteristics, suffered from the fact that the major blade stresses were taken by the relatively hot outer shell and additionally, the shell had to support the various types of insert brazed inside. The major deficiency appeared to be the uncertainty of the brazing techniques. Although the strengths of the brazed joints were theoretically adequate it is extremely difficult in practice to ensure 100 per cent complete brazing in a series of joints made simultaneously, and present inspection techniques are not a reliable safe-guard against imperfect brazing. As a result blade failures occurred on test. Indeed it might be said that the success or failure of blades fabricated from a number of component pieces rests essentially on the brazing or welding techniques. It would require an intrepid chief engineer to embark seriously on the production of engines having this type of blade at the present stage of the art. Nevertheless welding and high temperature brazing techniques are gradually improving, and fabricating methods of this sort certainly allow wide scope in devising suitable cooling configurations.

In experiments made in this country at the N.G.T.E. a slightly different approach has been followed—a serious attempt being made to preserve a relatively robust and solid construction with a minimum of welded or brazed joints, or even a complete elimination thereof. Of the various lines followed, four types stand out particularly and are illustrated in Figs. 14 to 17. The first is a virtually solid nozzle and rotor blade having a large number of small diameter passages of roughly circular cross section running spanwise through the blade. Due to the impossibility of drilling such passages in hard heat-resistant materials, a powder metallurgy technique was developed by G.E.C.[12]. Briefly, a block of metal (cobalt/chromium alloy) is compacted from powder, and fine cadmium wires are set in the block at points where holes are required. During sintering the cadmium volatalises and leaves clean, small diameter, passages. The blade profile and root are subsequently machined and ground out of the block. A set of blades of this type has been tested in an experimental turbine at the N.G.T.E. with promising success[12]. This turbine has been operated for a considerable number of hours at inlet gas temperature up to 1,400°K and no blade failures have occurred up to the present time. The quantities of cooling air used are roughly two per cent of the main gas flow for each row of blades.

Blades of similar form have also been produced on an experimental scale by casting techniques, using the "lost wax" process. Cores for the cooling passages

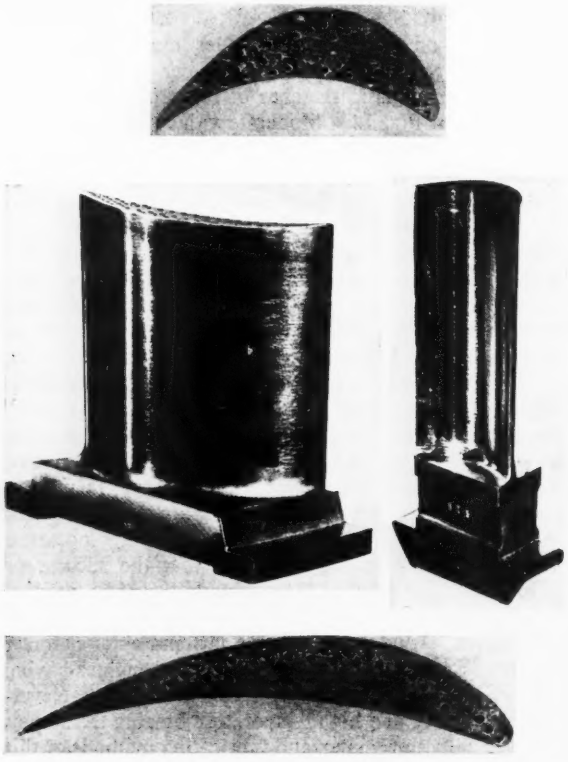

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FIGURE 14(*a*). Air-cooled nozzle and rotor blades produced from powdered metal.

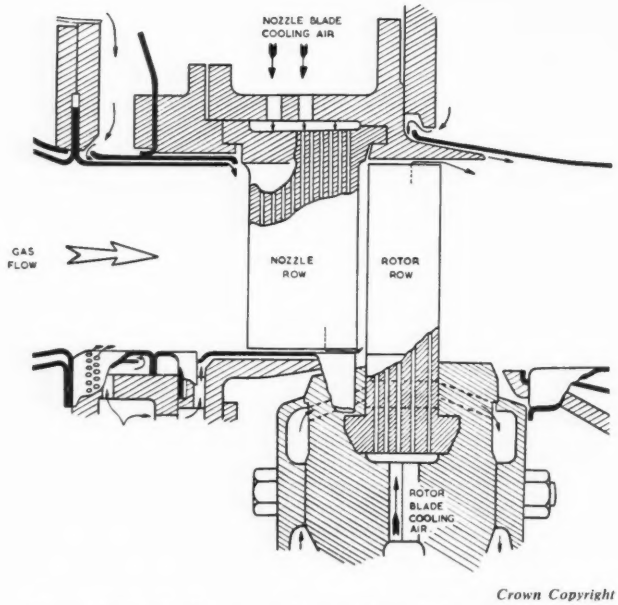

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FIGURE 14(*b*). Cooling system in experimental air-cooled turbine (N.G.T.E.).

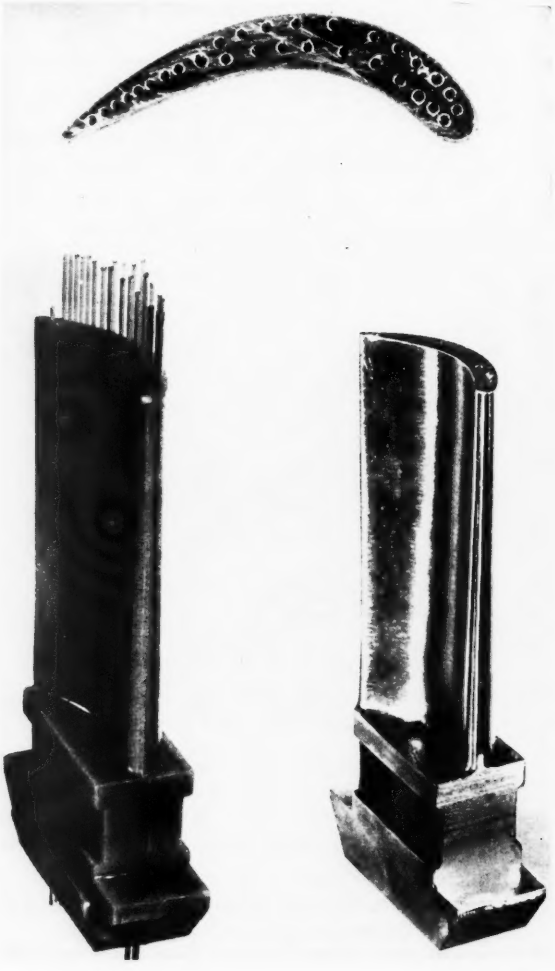

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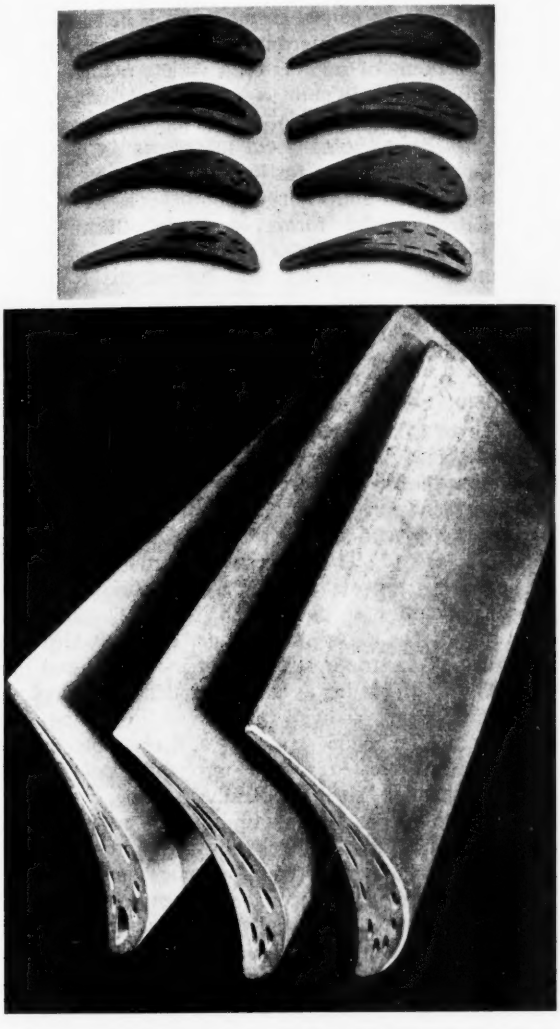
FIGURE 15. Air-cooled rotor blades made by casting using the " lost wax " process.

were formed of small diameter silica tubes, the silica being removed after casting by dissolving in hot caustic soda. This, too, is a promising technique, particularly for stationary nozzle blades. Use of the casting technique for the more highly stressed rotor blades is more problematical due to the questionable fatigue properties of cast materials as produced and inspected by current methods.

Another valuable and promising development is that of the extrusion techniques for the Nimonic series of materials[25]. By extruding and rolling strip blading from billets containing a number of drilled holes, a wide variety of blade sections containing cooling passages of roughly elliptical cross section may be produced. As mentioned earlier, the elliptical shape of cooling passage is highly advantageous in reducing the number of passages required and, hence, simplifying the manufacture problem. This technique is still in its infancy, but it clearly gives a wide elasticity in its application and augurs well for the future.



Courtesy of Henry Wiggin & Co. Ltd.

FIGURE 16. Sections of air-cooled blading produced by extrusion/rolling techniques.

The fourth technique is of the nature of a compromise[24]. A solid blade is machined by normal methods and a small number of relatively large diameter holes are drilled down the span. These holes on their own would allow only poor cooling, but high values of Z may be achieved by brazing inserts of various kinds inside the holes. These inserts may take the form of finned rods, spiral threaded rods, packed spheres, etc. Although brazing is required in this instance the stresses in the joints are low and relatively low quality brazing should prove adequate.

With all these types of blade structure Z-factors exceeding 180 have been achieved. In the last blade mentioned, with inserts of the type illustrated, a Z-factor of over 300 was achieved. This type of insert has the additional advantage that the "broken" nature of the passages will preserve a turbulent flow down to quite low cooling flow Reynolds numbers.

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FIGURE 17. Air-cooled blade with drilled passages and brazed internal secondary cooling surfaces.

8.4. COOLING CHARACTERISTICS OF TYPICAL INTERNALLY AIR-COOLED BLADES

It is impossible in this brief space to include a comprehensive account of the cooling characteristics of the many different types of internally air-cooled blades. Generally speaking, however, the characteristics of the sintered blades, which have been fairly exhaustively tested under actual turbine operating conditions, are typical of the type and these are illustrated broadly in Fig. 18. This illustrates the variation of average blade temperature with the quantity of cooling flow (uniquely expressed by the ratio of cooling air mass flow to main stream gas flow) and also illustrates the actual temperature distribution occurring in a blade. It will be seen that the actual cooling is far from uniform, the leading and trailing edges being very much hotter than the central "core" of the blade. This form of non-uniformity is very common and extremely difficult to combat. It arises due to the high local values of heat transfer to the blade at the leading edge and the

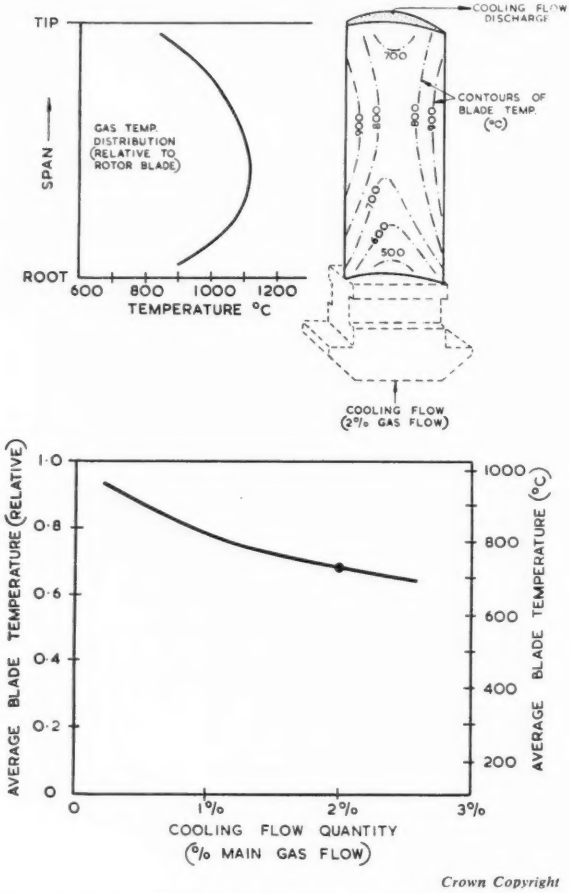

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FIGURE 18. Cooling characteristics of experimental air-cooled rotor blade. (Mean turbine inlet gas temperature $\simeq$ 1,380°K).

difficulty of placing an adequate number of cooling passages locally in the leading and trailing edge regions of the blade. This particular blade is relatively poor in this respect. In later blades the problem has been mitigated slightly by compromising the blade profile shape. More rounded leading edge shapes and thicker trailing edges help particularly. It is an interesting point of record, however, that these sintered blades have operated successfully despite the non-uniform cooling. The reason for this is attributed to the fact that the thermal stresses in the blade are compressive in the hot leading and trailing edges and tensile in the cool central region of the chord. When these thermal stresses are superimposed on the tensile centrifugal stress the resultant stresses in the hot parts of the blade are low and the major stress is carried by the cool central core. The net result, surprisingly, is that the predicted creep life of the blade differs little from that estimated for a uniformly cooled blade of the same average temperature. To achieve this, however, an appreciable degree of ductility in the blade material is demanded. A more comprehensive analysis of the characteristics of this blade will be found in Reference 12.

It is possible, perhaps, that on the strength of the limited experience gained so far we may be dismissing the importance of uniformity in cooling over-lightly. Only long hours of running on a variety of blades can eventually settle this point definitely, and indicate the extent to which the design of the blading may have to be compromised and complicated to achieve an optimum temperature distribution for long life in a cooled blade. It is possible that uniformity of cooling is less critical to the relatively solid forms of blade illustrated in Figs. 14-17 than to the less robust forms of blade fabricated for sheet metal, etc. Indeed, the N.A.C.A. have published data on an interesting series of experiments designed to improve temperature distribution in their fabricated blades. These followed broadly two lines of attack. Firstly the internal surfaces in a " tube-filled " blade shell (Fig. 12) were liberally plated with copper to improve the thermal conduction of heat within the blade. Secondly, a variety of slots were cut in various parts of the blade surface to provide a measure of film cooling over the hot leading edge and improved convection cooling towards the trailing edge (Fig. 19). Both these methods were partially successful in improving the temperature distribution but introduced difficulties so far as engine application was concerned. The use of thick copper plating (which has high density and poor strength) seriously reduced the strength of the blades as a whole. The film cooling techniques were relatively expensive in cooling air, complicated the blade structure, and the slots in the blade surface created a high probability of fatigue failure in the blade shell. Generally speaking, experience gained up to the present time supports the not unreasonable contention that for reliability an integral metal structure of blade is preferable to one composed of a number of component pieces joined together.

Before leaving the internally air-cooled type of blade a further important characteristic must be mentioned. This is its sensitivity to Reynolds number. In general, as the Reynolds numbers of the gas and cooling air flows in a turbine are simultaneously reduced, the internal rates of heat transfer in an air-cooled blade decrease at a slightly greater rate than the external (gas to blade) rates of heat transfer. This results in a tendency for the degree of cooling to worsen slowly with reduction in Reynolds number (the ratio of cooling flow to main gas flow being maintained constant) and has an important repercussion in the variation of the cooling characteristic of the blades in a turbo-jet engine with altitude. This will be discussed further in Section 10.

8.5. OTHER TYPES OF AIR-COOLED BLADE

Particular emphasis has been given to the straightforward internally air-cooled blade since it is believed that in the immediate future this is the most promising type for use in turbo-jet engines. Slight mention, at least, should be made of other methods, however. Film cooling, by introducing a thin stream of cool air at spacial intervals over the surfaces of the blades, has frequently been considered and experiments have been made in Germany, the U.S.A. and Great Britain. Interest has waned, however, for two reasons. With local

injection of cool air into the boundary layer the cooling is relatively inefficient due to rapid mixing of the cool air with the main gas stream. Furthermore, as mentioned already, the provision of slots in the blade surface weakens the blades, the ends of the slots providing unpleasant stress raisers leading to fairly rapid fatigue failure. Nevertheless, limited use of this technique has been found for nozzle blades (*e.g.* Reference 26).

Taking film cooling to the limit results in what is termed " effusion " or " transpiration " cooling, in which cool air is permeated outwards through a wholly porous blade skin[27]. In theory such a system should present a maximum of efficiency in cooling, since the cool air both cools the porous skin very effectively and at the same time the normal flow of cold air away from the surface reduces the rate at which heat can be transferred to the surface from the hot gas. This method of cooling is most attractive for cooling large areas of surface in combustion chamber flame tubes, jet pipes, etc., but its application to blade cooling raises many difficulties. These comprise:—

(1) Difficulty of providing a suitable porous material whose pore sizes are small compared with the thickness of boundary layers which occur on a turbine blade.

(2) Difficulty of achieving the variation in cooling flow per unit surface area around the blade profile which is ideally required (*see* Fig. 20). This difficulty is increased by the large variation in static pressure that occurs around the outer surface of a blade.

(3) The very difficult problem of manufacturing blades of robust construction incorporating a porous outer skin, porous materials inevitably possessing low strength properties.

Attempts so far to approximate to the ideal conditions (Fig. 21) have not shown very promising results[28], the degree of cooling actually achieved being little better than may be achieved with far simpler internally cooled blades having Z-factors in the region of 250. It is the author's view that the effusion technique is, perhaps, the most difficult method of cooling blades and still remains a long-term venture if, in fact, it materialises at all.

8.6. A GENERAL SUMMARY ON THE PRACTICABILITY OF AIR-COOLING

In turbo-jet engines flying at supersonic speeds in the vicinity of $M=2$ it has been indicated that, in theory at least, it should be possible to attain gas temperatures of about 1,400 to 1,500°K with quantities of cooling air bled from the compressor of the order of $1\frac{1}{2}$ per cent of the main mass flow for each row of turbine blades. To achieve this in practice requires that the blades have an efficient internal cooling system. This may be achieved simply with blades having a multiplicity of cooling-air passages running spanwise through the blades from root to tip. A good efficiency may be obtained in such blades if the cooling passages are of such shape and

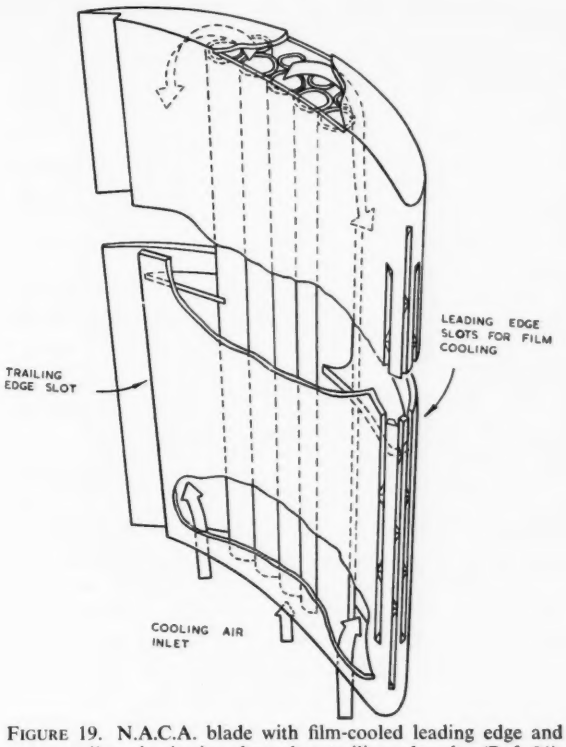
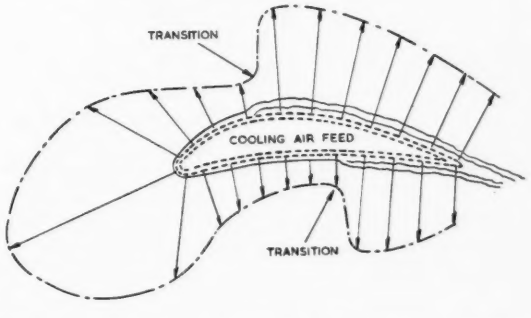
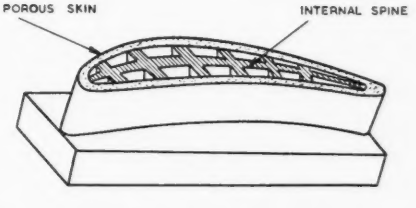


FIGURE 19. N.A.C.A. blade with film-cooled leading edge and some cooling air ejection through a trailing edge slot (Ref. 21).



(a) RELATIVE VARIATION IN FLOW RATE REQUIRED AROUND SURFACE TO ACHIEVE UNIFORM EFFUSION COOLING.



NOTE:- NON-POROUS INTERNAL SPINE GIVES REASONABLE STRENGTH AND PROVIDES FOR SOME CONTROL OF COOLING AIR DISTRIBUTION AROUND SURFACE.

(b) POSSIBLE CONSTRUCTION

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FIGURE 20. Effusion cooling.

design as to provide a value of Z-factor of about 200. In such blades the available capacity in the cooling air for absorbing heat is used with an efficiency of, roughly, 75-80 per cent. In the view of the author this is a reasonably practicable compromise between overall cooling efficiency on the one hand and difficulties of blade manufacture on the other. With manufacturing techniques which are now under development it seems reasonable to expect that the production of cooled blades of this efficiency will not prove too onerous a task.

In the light of this it is apposite to conclude this paper with some brief speculation upon the repercussion that air-cooling may have on the aerodynamic design of the turbine stages and the general potentialities of air-cooled turbo-jet engines as applied to high speed flight.

9. Choice of Turbine Design

During past years the aerodynamic efficiencies of the turbine components of jet engines have steadily improved, this improvement being obtained largely by increasing the blade reaction (and the number of turbine stages) and to a lesser extent by reducing the axial velocity of the gas stream through the blades. The introduction of cooling will tend to reverse this trend.

To acquire the maximum amount of cooling for a predetermined quantity of cooling air and a predetermined cooling passage configuration (*i.e.* Z-factor) it has been indicated in Section 8.2 that it is necessary to reduce as far as possible the total external surface area of the blades. This necessitates reducing the number of stages to a minimum (and hence reducing blade reaction), increasing the pitch/chord ratio of the blades, and reducing the gas flow outlet angles from the blade rows. To obtain a good cooling passage configuration within the blades it may also be desirable to modify present blade shapes by using rounder leading edges, thicker trailing edges, and reducing the amount of twist along the blade span. Unfortunately all these requirements, desirable to achieve good cooling with a minimum of cooling air, tend to reduce the expansion efficiency in the turbine. In practice, therefore, it will be necessary to strike some compromise between high turbine expansion efficiency on the one hand, and the quantity of cooling air required (and associated losses in engine performance) on the other, in order to obtain an optimum overall engine performance.

It is impossible to generalise upon the best compromise since it will inevitably depend upon the particular duty for which the engine is designed. A single example might be quoted, however. Fig. 22 compares the performance, for a flight speed of Mach number 2 in the stratosphere, of engines having respectively a single-stage turbine of low aerodynamic efficiency (82 per cent assumed) and a two-stage turbine of higher aerodynamic efficiency (88 per cent). So far as overall performance is concerned it will be observed that the differences between the two designs are only marginal, and at very high gas temperatures the low efficiency single stage turbine may be slightly the better so far as specific thrust is concerned. Fig. 22 also

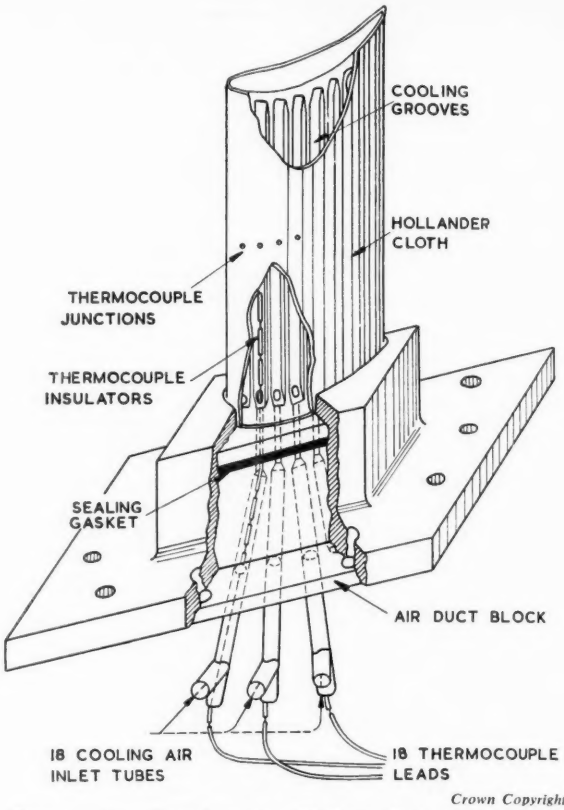

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FIGURE 21. Experimental effusion-cooled nozzle blade (N.G.T.E.).

compares the performance of the air-cooled engines with that of the ideal uncooled engine. Roughly speaking, the gain in thrust achieved in an air-cooled engine by raising the gas temperature amounts to about 80 per cent of that which would be possible if cooling (with its associated performance losses) could be eliminated.

The example shown in Fig. 22 is in no way rigorous and must be regarded as illustrative only. It serves to demonstrate, however, that in jet engines designed for supersonic flight a saving in cooling flow extracted from the compressor of one per cent of the engine flow may be worth the sacrifice of roughly three per cent in turbine efficiency, on a basis of net specific thrust. This is sufficient to show that it may be well worth compromising the turbine blade shapes and efficiency a little if, by so doing, the cooling air quantities can be substantially reduced. For aircraft engines the weight of the turbine assembly must also, of course, influence the eventual compromise and this aspect may also favour a reduced number of stages and lower turbine efficiency.

10. Potentialities of Air-Cooling

As an illustration a general study has been made relating to engines propelling hypothetical supersonic aircraft at speeds up to a Mach number of 3 over a wide range of altitude. In all instances it was assumed that

the engine sizes were such as to swallow approximately 300 lb. of air per sec. at maximum rev./min. at S.L.S. conditions, and a S.L.S. compression ratio of 6:1 was assumed. The air intakes were supposed to be of the conical centre-body type. The turbine had two stages and a mean rotor blade temperature of 820°C was assumed. The blades were cooled by air bled from the engine at compressor delivery pressure and temperature, the blade cooling passages being designed to permit reasonably good cooling (*Z*-factor of 200) and to pass a quantity of cooling flow per row of blades of roughly $1\frac{1}{2}$ per cent of the main engine gas flow. These conditions were sufficient to impose a maximum permissible value to the turbine inlet gas temperature at each flight condition. These inlet gas temperatures over a wide range of flight speed and altitude are plotted in Fig. 23.

It will be observed that at any given flight speed the maximum permissible gas temperature decreases as the altitude increases. This arises from the corresponding reduction in the flow Reynolds numbers in the engine, which leads to a reduction in the degree of cooling that may be obtained. The magnitude of the drop in cooling with increasing altitude is a little uncertain, due to the uncertainty of the rate of variation of gas to blade heat transfer coefficient with Reynolds number (dictated by the value of the Reynolds number exponent x, Fig. 7). It is conceivable that a greater area of turbulent boundary layer will occur on the blades than has been supposed in the present analysis and this would result in the lines in Fig. 23 becoming nearer to horizontal, the values of gas temperature in the middle of the altitude and speed range remaining much the same as shown.

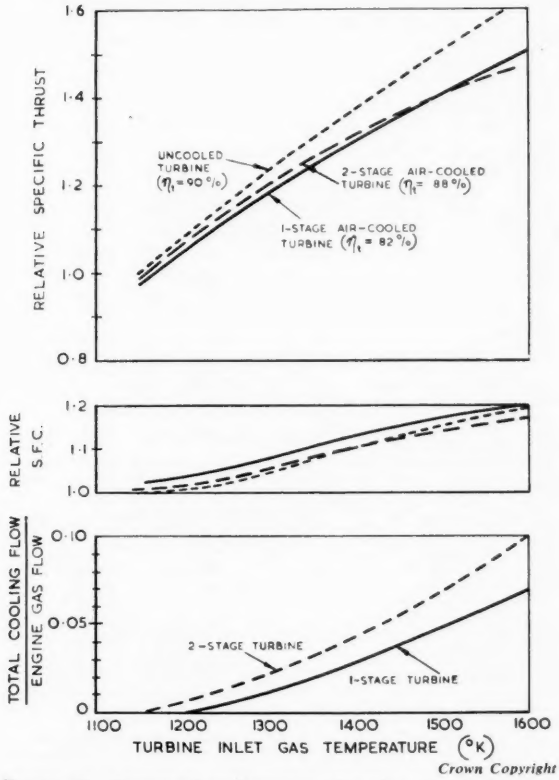

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FIGURE 22. Compared performance of engines at $M=2$ in the stratosphere with (*a*) single-stage (low efficiency) air-cooled turbine and (*b*) two-stage (high efficiency) air-cooled turbine.

[Values of thrust and fuel consumption are shown relative to those for an uncooled engine at 1150°K gas temperature. S.L.S. compression ratio ≃ 6:1.]

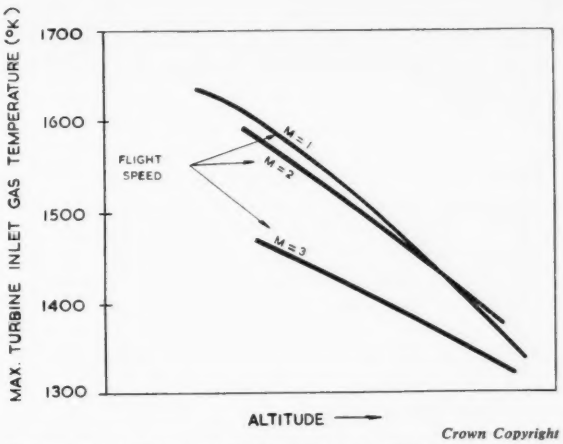

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FIGURE 23. Influence of flight speed and altitude on maximum permissible gas temperature in a turbo-jet engine with air-cooled turbine blades.

[Cooling air at compressor delivery temperature mean rotor blade temperature ≃ 820°C.
Rotor row cooling flow ≃ 1·5 per cent engine air flow.
Engine swallowing capacity ≃ 300 lb./sec. (S.L.S.).]

An incidental factor arising from the influence of Reynolds number is the question of choice of engine size. If the present data is realistic then, so far as cooling is concerned, there is an advantage in designing relatively large engines. For example, a reduction in engine size from 300 to 100 lb. of air per sec. would possibly necessitate a reduction in gas temperature of about 40°C.

As flight speed increases at a fixed altitude the stagnation temperature of the air entering the engine increases, leading to an increase in the cooling air temperature and hence to a reduction in cooling. This is partially counterbalanced, however, by an increase in flow Reynolds number as flight speed increases which tends to improve the degree of cooling. The result of this is that over the lower range of flight Mach numbers there is little change in maximum permissible gas temperature, but at high flight Mach numbers the permissible gas temperature falls appreciably.

It is an unfortunate, but apparently inherent, characteristic of air cooling (as applied in the simple manner considered in this discussion) that it becomes more difficult to obtain a high degree of cooling as flight speed and altitude rise—a tendency which is the reverse of that ideally required. As explained, part of the trouble is that at very high flight speeds the temperature of the cooling air bled from the compressor becomes high. An obvious remedy which suggests itself is to chill the cooling air before it enters the turbine blades, although this must necessitate some penalty in weight

and drag. This, however, is looking well into the future and it may be some time yet before engine development reaches the stage at which such techniques are required.

11. Conclusions

Having glibly shown a graph illustrating engine gas temperatures rising in some circumstances to as high as 1,600°K, it becomes necessary to qualify these figures. These temperatures illustrate the rough limits that may be set by the blade cooling problem alone, and perhaps give an optimistic picture for the future. It may be anticipated that in practice the upward climb of turbo-jet flame temperatures will be gradual, and they are unlikely to approach the values shown in Fig. 23 for a considerable time to come. The problems of large scale production of both efficient and reliable cooled blades are by no means wholly solved as yet, although several pointers are now clearly discernible, and plenty of hard practical experience must be gained in the production shops and on the test bed before the high temperature turbo-jet engine becomes a reality. Furthermore, the design of combustion chambers and jet pipes must be adjusted and finally proved to operate reliably and satisfactorily at the raised gas temperature levels.

This will provide a story which must be told in future years. Such work as may be recounted now is that which has been going on quietly during past years in the research laboratories in anticipation of such development—and even this may yet be only partially unfolded. It is hoped, nevertheless, that the paper has given a slight glimpse of this work and indicated broadly some of the potentialities of the high temperature engine.

At the present time the most significant practical achievement recorded is, perhaps, the successful operation of an experimental air-cooled turbine at gas temperatures up to 1,400°K. This has been accomplished in the relative comfort of an N.G.T.E. research laboratory and is well removed from a jet engine propelling an aircraft at high speed about the sky. It is, however, an encouraging demonstration, and clearly hints that a rise in engine gas temperatures of at least 150-200°C should not be too much to expect in the early phases of development.

In fact, the engine temperatures that appear to be within grasp by simple air-cooling seem very satisfactory—at least for propelling long-range aircraft at supersonic speeds up to about a Mach number of 2.5. Other shorter range high speed aircraft must also benefit materially. Indeed, there can be no doubt that this development broadens importantly the ultimate scope of the turbo-jet engine and the supersonic aircraft it will propel.

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DISCUSSION

H. PEARSON (Chief Research Engineer, Rolls-Royce Ltd., *Fellow*): He congratulated Mr. Ainley on an extremely able and interesting lecture on the cooling of gas turbine blades. His pioneering work in this field, as exemplified in the successful running of an experimental wheel at gas temperatures of 1,400°C, was already widely known to those with any direct interest in this type of work, nevertheless it was a privilege to give public recognition to it here. Further, he had laid down, on a very good technical basis, the fundamentals of the whole subject with methods of computation such that anyone could take up the subject and rapidly calculate the cooling to be achieved by any proposed system.

Surely this was another happy example of the correct relation between Government and Industrial Research. He was reminded of Howell's great achievement in laying down the foundations of Axial Compressor Theory at just such a date that its results could be rapidly applied by Industry. In congratulating the lecturer, therefore, he would also like to include the N.G.T.E.

The layman might be tempted to ask why practical blade cooling had been so long in coming, seeing that the Germans were using it in the late war. It was a difficult question to answer, undoubtedly largely due to the fact that until recent years little work was proceeding. This was not due to wilful neglect, but to the fact that turbine blade materials were improving at roughly a good enough rate to suit the temperatures required. On jet engines at present aircraft speeds, high temperatures resulted in such an increase in fuel consumption that their use was doubtful. In any case, large strides in specific engine weight were already being achieved by quite other means. This process had come rapidly to a stop but the main incentive for high temperatures came from the wish to operate at high supersonic speeds.

Nevertheless, during all this time the locusts had not eaten completely undisturbed. Work in the firms had been quietly proceeding, both in testing aerodynamically on rigs and running blades experimentally in engines, and more particularly in investigation of different manufacturing techniques. The lecturer had indicated that the latter would be one of the chief factors in the type of cooling system used. Broadly speaking, they considered cast blades to be a bad proposition for the rotating blades, although satisfactory and standardised for the stationary nozzle guide vanes. Thus cast multi-hole blades for these latter should be readily usable, although unless holes could be got very near to the trailing edges some form of film cooling might be required. The latter had been found necessary with more simple cooling systems.

For rotating blades some form of forging or extrusion technique was at present thought to be the best method for preserving the best metal characteristic. They were naturally reserved about the prospect of sintered blades, but were willing to try.

Mr. Ainley had mentioned non-uniform cooling of the blade chordwise and one reason why this was not so serious as might be supposed, was that the cool mid-section of the blade took the load and the hot parts were actually reduced in stress. One objection, however, was that with repeated heatings and coolings the thin trailing edge both cooled and heated quicker than the mid-section and fatigue cracks could occur. This was a straightforward problem which was being closely watched.

Mr. Ainley had shown that better cooling could be obtained by compromising the turbine design—*i.e.* take out half the blades and the problem was halved. Take out all of them and use a ram-jet and the problem was completely solved! It was true that reduced turbine efficiencies did not have a marked effect at high supersonic speeds, but that was only one side of the question. For fighter aircraft a reasonable subsonic cruising performance was required and even on long range supersonic aircraft one had to take-off and climb. He remembered seeing some early air- and liquid-cooled blades in America in which the external blade shape appeared to have been drawn around the cooling holes. He would have guessed that any benefits in cooling would have been lost in reduced efficiency. This point applied to the lecturer's remark about increasing blade trailing edge thickness so that it could be better cooled. They had found this to have a shocking effect on efficiency.

He thought that one possible attraction of, say, a liquid sodium system could be emphasised. Generally speaking, the difficulty in cooling blades was to provide enough internal surface area. If liquid sodium were used this was no longer a problem and heat could be led out to the root with little temperature drop. If

extended roots were used these might be suitably finned and the cooling air led over them. Thus all the disc cooling and sealing air could be used, there were no narrow holes to be kept clear of dirt, and so on, since the internally filled sodium holes were sealed off permanently. He would like the lecturer's comments on this system.

On most of Mr. Ainley's heat transfer data he was in good accord but some of Mr. Ainley's admittedly optimistic predictions of permissible gas temperature seemed to him to be difficult to achieve, because in practical engine designs it was always a problem to lead the cooling air to the base of the blade without large pressure losses. This meant that the cooling would be restricted by the amount of cooling air that could be fed up the blade, as well as by the amount of heat it might pick up on the way. This was one of those practical matters difficult to discuss in general terms, but he felt it would be the chief limitation to the achievement of high degrees of cooling. He found it difficult to see just at the moment how they could expect 1,400 or 1,500 degrees at Mach numbers of the order of 2 to 2·5.

He was amused at the proposal made to Mr. Ainley for having water-cooled blades. He was a bit surprised because it reminded him of a similar suggestion made early in the days of jet propulsion, that motor cars could be made with four jets of air, one at each corner, and perfect suspension would be obtained. Everybody laughed but now they were doing something rather similar, but not with motor cars. Mr. Ainley, however, said that torque could not be got by radial jets of water. He thought he should talk to Mr. Davidson.

DR. H. COHEN (Cambridge University, *Associate Fellow*): Following on what Mr. Ainley said about the disadvantages, as he saw them, of using a liquid-air system—that was, a primary liquid in the blade and then secondary air cooling—there was a further factor to be considered. This was the fact that in cooling by the passage of air straight through the blades, air at a pressure higher than the ram pressure and consequently at a higher temperature had to be used because it would be discharged at the tips of the blades where the pressure was greatest in the turbine annulus. With the liquid-air system it would be possible to use air at the ram temperature, or perhaps slightly higher, to allow for the extra losses to get the air through to the secondary coolant surface.

There were many minor matters which came to mind on hearing and reading Mr. Ainley's paper. One thought about such factors as the effect of the twist and taper of the blades, which had not been mentioned and the effect of clearance on the turbine performance. He felt that that sort of argument about how those things were going to affect adversely the design had been aired long enough. Mr. Pearson had said that the engine manufacturers had been watching and waiting, if he interpreted his remarks correctly, for the sort of information which Mr. Ainley and his colleagues at N.G.T.E. had produced.

He agreed entirely with Mr. Ainley that a simple and direct air-cooling system of the type he advocated should be the first practical application. It must be difficult enough; they had been talking about this now for rather more than 10 years and he would like to hear (from people in the engine firms), something about when they were going to make an all-out attempt at a fully-cooled turbine unit with all the other additions that would be necessary to the sort of turbine that was thought about now, such as cooled combustion, systems, nozzles and so on. It was only by such an undertaking that they would discover whether the information required for design had already been provided. He did not think that talking about it much further at this stage would advance the development any more.

P. GROOTENHUIS (Imperial College, *Associate Fellow*): He was most impressed by this figure of the heat delivered to the blades as being equivalent to about a ton of water that had to be evaporated per hour. It seemed very large to him. In the conventional cooling techniques this was allowed to get to the exposed surfaces of the blades, was then taken away on the inside and preferably returned to the jet at the end of the turbine. The aim of a cooling expert should be to prevent that heat getting to the surface of the blades at all, by putting a heat barrier between the hot stream and the blade and he was sorry to see that Mr. Ainley had dismissed rather quickly the one method which could do that; either film or effusion cooling. He knew Mr. Ainley wanted to bring forward the experiments which had been done at N.G.T.E. but it seemed a pity that it had been dismissed so quickly because, although it might not be today's way of obtaining cool turbines, it might well be that for yet higher flight speeds, they had to do even better than the present suggestions. Stopping the heat getting to the blades was like winning half the battle.

Mr. Ainley suggested using about 1·5 to 2 per cent cooling air per blade row. This seemed rather large, and as Mr. Pearson had said, to get the air there might be quite a problem. It was beneficial to reduce the flow of cooling air fom 2 per cent to one or less than one per cent, even for only some of the blade rows. He therefore called upon an engine firm to be courageous enough to build a turbine with the stators effusion-cooled. He suggested that even today one might, if one were courageous enough, make effusion-cooled stators which needed perhaps only about three-quarters per cent of cooling air per row. Why was it dismissed? It seemed that Mr. Ainley relied very much on the *one* blade rig experiment with effusion cooling done at the N.G.T.E. and he showed a picture in Fig. 21. It was a very interesting experiment but it was only one rig test and he would like to ask, did he think that was sufficient? Many people had shown in print and otherwise that there was an advantage in this method, was it not worthwhile doing a few more rig tests? If they were all as disappointing as that one test at the N.G.T.E. then they had a good argument for throwing the method overboard but if with a different technique, which had been suggested, one could get an improvement one had the sort of background data to build into an engine.

Another point which needed to be considered was that the blades, as suggested by Mr. Ainley, discharged their cooling air into the main stream at the tips. That was the worst place for getting any use out of that air in any subsequent stages. By ejecting the cooling air along the blade or better still, by effusion cooling over the whole surface, the air, although it was at a slightly lower temperature, did do work or was able to do work throughout the next stages. Calculations, as given elsewhere* showed that the losses were not as high as might at first be thought. He was sorry to see that the method of effusion cooling had been dismissed so readily, although there was plenty of opportunity either for more sums or for practical work.

J. L. EDWARDS (Chief Combustion Research Engineer, de Havilland Engine Co. Ltd, *Associate Fellow*): The discussion so far had been interesting, but he was a little surprised at some of the things that had been said, as for example the emphasis on the lack of courage of engine companies to put cooled blades in their engines. It did not take much courage to put an experimental component in a test bed engine and most engine companies were quite used to such components coming out again—in many cases prematurely and of their own volition. Such tests, however, did involve the manufacture of expensive and complicated components and the work was not lightly undertaken if implied advantages were negatived by consequent disadvantages. Mr. Ainley had shown a number of blade sections and blade forms which from the point of view of cooling were ideal. When one compared these blade sections with those in current use today he must agree with Mr. Pearson that they would be inefficient and very heavy.

A "Z" factor quoted by Mr. Ainley would ideally produce a blade with many very small cooling holes. Although highly efficient heat exchanges, one could not but feel that operation of engines in which the turbine blades were cooled by such very small passages would be most dangerous in dusty climates. Presupposing that maximum gas temperatures of the order of 1,400°K were used for take-off, then a blockage of a number of these cooling passages by dirt would have rapid and catastrophic effects on the turbine blades. His own view was that no cooling hole should have a minimum dimension less than 0·050 in. to 0·060 in.

One other point on which he wished to comment was Mr. Pearson's statement that the development of the high temperature engine had been held back by the combustion chamber. When a new and possibly high temperature engine was conceived the compressor and the turbine were designed on the basis of information obtained by theoretical study qualified by experimental results and an efficiency of 85-90 per cent was considered good. The size was dictated by the arithmetic and mechanical design considerations and it was unheard of for somebody to say that these components were much too big and must be cut in halves forthwith. The combustion system was in a much less fortunate position. As a rule the combustion engineer was presented with a space diagram and some figures worked out by the compressor designer and told that he must get his combustion chamber within that space. If he grumbled and said the velocities were too high and he would like his chamber diameter to be greater than the compressor and turbine, then he was informed that that was not permitted and he was holding up the development of the engine.

Combustion systems, unfortunately, did not lend themselves to detailed mathematical treatment. The air flow pattern was involved and somewhat random and consistency of air flow and fuel distribution was most difficult to achieve. Such results as were obtained were largely the result of experimentation and suffered naturally from experimental scatter which evidenced itself in variations of the gas temperature presented to the turbine, even between different chambers of the same design.

The turbine engineer must accept this state of affairs. He was not entitled to design his turbine on the basis of a uniform entry temperature and he might even be unduly conservative with a 10 per cent. variation. Having accepted these limitations however he could step up the average temperature at outlet from the combustion chamber by as much as his turbine would stand.

As he was sure Mr. Pearson must know, combustion chambers could easily be designed to produce average temperatures which would cause any turbine in production today to stretch its blades with the greatest of ease. While one must accept a limit on the combustion system as regards temperature distribution, he saw no difficulty in producing mean temperatures far in excess of anything which could be used.

Those remarks might be a little irrelevant to Mr. Ainley's cooled blades, but he thought they were pertinent to the evolution of the high temperature engine.

As he interpreted the curves, Mr. Ainley suggested that they could ultimately run the turbine at a gas temperature of 1,500°K. At an aircraft Mach number of about 3·0 and with 2 per cent cooling air per blade row this would involve a metal temperature of about 130°K. In practice it was unlikely that the blade temperature could be further reduced by cooling and the only way of obtaining further improvement was, as a previous speaker said, to stop the heat going into the blade. Did Mr. Ainley foresee any possibility of coating his blades with some insulating medium?

Another point involved the engine reheat combination. It was possible to attain a given thrust with a relatively cool engine and high degree of reheat. Increasing the turbine temperature did little to change this maximum thrust, although it gave some improvement in economy. Did Mr. Ainley think there was an optimum turbine temperature beyond which it would be profitless to go?

DR. E. S. MOULT (de Havilland Engine Co. Ltd., *Fellow*): There had been a suggestion in what had been

* P. GROOTENHUIS. General discussion on Heat Transfer. *Proc. I. Mech. E.*, p. 485, 1951.

said that the constructors of turbine engines in this country had been slow in taking up cooled blades. Perhaps they had been a little cautious, but a good deal had been done and the results of their current development work would be apparent before long.

The major delay in bringing cooled blades to fruition was, as Mr. Edwards had pointed out, the manufacturing problem. In the meantime they had been well served in this country by the metallurgist who had given successive improvements in blade alloys and, on the whole, kept pace with engine development.

However, he felt they were coming to the end of what could be done with normal forged alloys. Even if they found new ways of improving their heat-resisting properties they might not be able to forge them. He hoped therefore that research would continue in cast alloys, in new materials and in protective coatings. In the end they would probably need the best materials *and* air-cooling if they were to work at stoichiometric fuel/air ratios.

The effects on performance of increasing the turbine-inlet temperature at a speed of Mach 2·5 in the stratosphere are shown in Fig. A. It would be seen that thrust (without reheat) rose rapidly with turbine-inlet temperature but remained more or less at its present value if reheat were used. On the other hand, at these speeds consumption, in the non-reheat case, rose only slowly with advancing turbine temperature. The consumption with reheat was always greater than for the plain engine. As temperatures within the engine advanced towards the limit, the thrust boost from afterburning naturally became a smaller percentage and the differences in consumption, much reduced. In fact, at even greater flight speeds than that referred to in the diagram, all air-breathing engines approached the case of the ram-jet. This was because they were then combusting all the available oxygen at good efficiency by virtue of a high ram-pressure ratio.

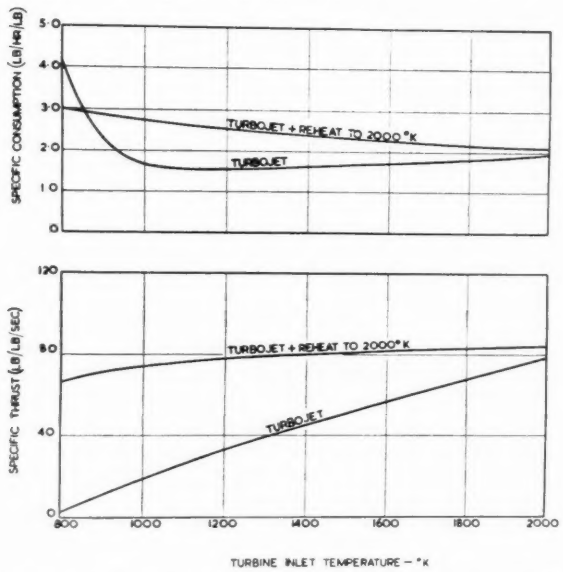

FIGURE A. Effect of increasing engine temperature. Mach No. 2·5—40,000 ft. altitude.

Reverting to the use of hollow blades, most of their engines already employed hollow nozzle guide vanes for the turbine and they had found that the mere fact of making them hollow evened out the sectional thicknesses and the temperature differences that arose in operation. These blades were now being air-cooled with advantage and they expected similar improvements with rotor blades working at yet higher gas temperatures. It could be shown that there was as good, or a better, case for the use of high turbine temperatures with a plain turbo-jet for long-range flight at really high speeds than a short-range fighter with reheat. Moreover, as Mr. Ainley had pointed out, great advances in power and economy were possible by raising the turbine entry temperature in the case of the turbo-prop application.

Perhaps more could have been said in the matter of blade stressing which, for high-temperature operation, was the Achilles heel of all aircraft gas turbines. If the modified construction necessary to permit cooling raised the stress level in the blade, then it was insufficient to cool it to the same temperature as applied with the original solid blade. For the same working factor of safety the metal temperature must then be lower than with the uncooled blade. Thus, it was easy to enter a vicious circle of higher stresses and the need for yet more cooling. Since cooling involved some loss of efficiency, the net result might be an engine with cooled blades but with little gain in overall performance.

In general one tended with cooled blades to thicken the tip sections and this increased the centrifugal load on the roots. The roots themselves were weakened by the air passages (or unduly thickened—which dropped the turbine efficiency). Theoretically, one should be able to maintain the desired taper ratio in the length of the blades, and so control the stresses—but it was not easy and was a point which must be watched.

Built-up blades fell into two classes, those with a strong outer skin and a filler block in the centre acting as an air deflector and those with a strong spine with a light sheet-metal covering brazed or welded to it. In either case, unless the design was carefully done and the load carefully shared, the filler block might over-load the skin or the loose skin might over-load the supporting spine.

He did not wish his remarks to cause any despondency or discourage in any way the development of the cooled turbine: he merely wanted to high-light some of the problems that beset them and indicate why an entirely satisfactory solution had taken a little time. With advancing aircraft performance, cooled blades were wanted very badly and if, in the next few years, they could cool blades by 100°-200°C and increase gas temperatures correspondingly, they would have achieved a great deal. In fact, as Mr. Ainley had pointed out, this represented a greater advance in working temperature than they had realised during the 10 to 15 years since the aircraft gas turbine began.

MR. ROWE (*President*): No one rose to the bait that was thrown out about the propeller-turbine. It was true that the paper was on the high temperature turbo-jet engine but it seemed to him that the problems on

the turbine propeller might be rather different and might be much more difficult.

They had had an excellent lecture, a first-rate discussion and he thought they all admired the way in which Mr. Ainley delivered his summary.

P. C. H. WHITE (Handley Page Ltd., *Associate Fellow*) *contributed*: Figure 2 and Section 2.1 of the lecture indicated that high turbine inlet temperatures were necessary for economic flight at supersonic speeds. Fig. 23 showed that cooling of the turbine blades using air direct from the compressor would not, in fact, enable the optimum turbine inlet temperature to be obtained above a Mach number of 2·0.

Would Mr. Ainley care to comment on the following other solutions with which they appeared to be confronted when considering turbo-jets as power-plants for flight speeds in excess of Mach number 2·0?

(*a*) By-pass some compressor air through a refrigerator and thence through the turbine blades, thus obtaining the cooling necessary to use the optimum turbine-inlet temperatures of Fig. 2.

(*b*) Use ram-air (perhaps from the main intake) to cool the blade roots and cool the blade by a closed circuit liquid system as suggested by Mr. Pearson earlier in the discussion.

(*c*) Be content with the maximum temperatures which the normal blade cooling would give as shown on Fig. 23.

B. D. BLACKWELL (Bristol Aero-Engines Ltd., *Associate Fellow*) *contributed*: Listening to the discussion, he had formed the opinion that the problem ought rightly to be divided into two parts; the first was the case for the cooled turbine and the second, the practical means of achieving it. He felt that Mr. Ainley, who had probably done more for cooled turbine development than anyone else he knew, had done it less than justice in the case he had made for its use. Firstly, he would have thought it unwise to confine the first dissertation on cooled turbines before the Royal Aeronautical Society to the turbo-jet applications. The outstanding case for the cooled turbine could be made for the turbo-prop and high augmentation ratio ducted fan engine. Mr. Ainley had selected the most difficult and controversial field of engine development as the basis of his case. The cooled turbine supersonic engine was in a very similar (unenviable) position to the ducted fan engine. It was jammed between two well-established means of propulsion, and had only marginal advantages in relationship to either. In other words, the 1,200°K unreheated, uncooled jet engine and the full reheated 1,200°K jet engine flanked it in the same way as the turbo-prop and turbo-jet flanked the ducted fan, and he would not dwell on the consequences this had had for the ducted fan!

As he saw it, the case for the cooled turbine in the supersonic field rested on the marginal advantages in specific fuel consumption which it offered over the reheated engine at the same thrust. These advantages were marginal because, even with the cooled turbine, some measure of reheat would be required. However, he did understand that marginal advantages of fuel consumption were in fact likely to play a vital part in supersonic flight, but it would require a much deeper argument than Mr. Ainley had presented to show them up. He felt it would be desirable one day to hear from the aircraft side their views on this matter.

When the case for the cooled turbine was presented in this manner it seemed a natural corollary not to depart substantially from current engine practice, either with regard to turbine efficiency or methods of construction. He knew Mr. Ainley would not like this but with his own eyes fixed firstly on the turbo-prop and, secondly, on the marginal advantages of the cooled turbine supersonically, he felt Mr. Ainley's doctrine was extremely dangerous unless a complete analysis of the particular application had been made. Even then, industry had to watch the possibility of deriving engines for a number of applications from a basic specification, and it would be a long time before they would dare to commit the turbine design to the radical treatment in terms of the blade shape pitch chord ratio and number of stages which Mr. Ainley advocated.

He would like to draw attention to the overwhelming importance of manufacturing technique development in this field. It might not be realised that the production of solid turbine blades was far from being satisfactorily solved, and that the manufacture of blades with "arty-crafty" cooling passages could be the "straw that breaks the camel's back" unless designers did a lot more than just draw the shapes they required. However, team work with manufacturing experts was paying dividends and a number of satisfactory lines of development were opening up. The story of those would no doubt be told in due course before the Society.

MR. AINLEY'S REPLY

MR. PEARSON: He thanked Mr. Pearson for his kind opening remarks. His suggestion that the work recorded in the lecture was a happy example of the correct relation between Government and Industrial Research was particularly cheering. He sincerely hoped that this was true, and that a start on the development of cooled turbines had not been delayed by Industry awaiting any lead that they had attempted to give! Many people had felt that the development of cooled engines might have begun earlier than it apparently had, and some of the reasons advanced in denial of this did not appear wholly convincing. For example, the suggestion that on jet engines at present aircraft speeds high temperatures resulted in undesirably high fuel consumption was a little paradoxical in light of the fact that considerable use had been made of reheat for thrust increase at a much higher rate of fuel consumption. However, that was now past history. The important thing was that development was now under way—and the problems immediately facing them were more important.

At the present time he would agree with Mr. Pearson's philosophy concerning the use of cast blades, although he preserved an open mind about their more distant future prospects.

He appreciated Mr. Pearson's concern regarding the compromises in turbine design and turbine aerodynamic efficiency that he had advocated, but felt that such compromises would be found inevitable. In uncooled turbines they had become accustomed to light weight designs having long slender blades. Because of the development of light weight stages the optimum designs for maximum engine power to weight ratio had shown a steadily improving aerodynamic efficiency. Mr. Pearson suggested that it might be difficult to pass something of the order of 1·5 per cent cooling air through cooled turbine blades with the pressure differences available and also, that poor chordwise temperature distributions in the blades might lead to mechanical failure by thermal shock. If they attempted to cool blades without modifying current blade forms and aspect ratios, this would certainly be true. Precisely for this reason it might be necessary to reduce blade aspect ratios, in order to pass the required cooling flow quantity, and to modify blade form, to reduce chordwise variations in blade temperature. Those were perhaps the only means of achieving the high engine gas temperatures about which Mr. Pearson expressed doubt. The inevitable effect of those modifications would be to increase the stage weight of the turbine since low aspect ratio meant larger blade chords, heavier blades, and heavier discs to carry them. This fact, coupled with the desirability of minimising the total cooling air quantity, would render it necessary to cut down the number of turbine stages to such a point that they achieved an optimum high temperature cooled design to give maximum power to weight ratio. He was only suggesting that when they found this optimum the resulting stage aerodynamic efficiencies would be rather lower than those to which they had become accustomed on uncooled turbines.

The suggestion that they might use a liquid sodium cooling system for transferring heat to an extended and air-cooled blade root appeared at first sight to offer some attraction. Such schemes had not been overlooked. The difficulty that arose was in providing a design of air-cooled root which possessed the necessary attributes of large surface area and high heat transfer coefficients on the air side. The liquid metal cooling system in the blades might permit high blade aspect ratios to be used, but this advantage was offset by the fact that the air-cooled root would be relatively large and clumsy and necessitate relatively heavy discs to carry it. Moreover, the problems of blade manufacture were likely to be more difficult rather than easier than those appertaining to internally air-cooled blades. On balance, therefore, he doubted whether such a scheme would show to advantage. At the best it would seem that any advantage might be only marginal.

DR. COHEN: The advantages suggested by cooling the extended roots of liquid metal filled blades with ram air were unfortunately offset greatly by the fact that the ram air had a relatively low pressure and density. Firstly, the fact that the ram air would be at an appreciably lower pressure than the main gas stream, introduced a difficult sealing problem at the disc rim, since it would be essential to prevent any of the hot gas leaking into the ram cooling air in the vicinity of the blade root. Secondly, he had already indicated that a difficulty in the root cooling system was in minimising the bulk of the air-cooled blade root. This required the cooling air to be at a high density and as high a pressure drop as possible should be available for pushing the cooling air through the root. In fact the problems were virtually the same as those applying to the design of a good internally air-cooled blade. Thus, use of low pressure ram air could only be an embarrassment, if a substantial degree of cooling were to be achieved, and he was confident that it would show to less advantage than using some of the compressor delivery air.

With Dr. Cohen's further remarks he agreed wholeheartedly. They had indeed spent considerable time arguing about the importance of factors such as blade twist, thick trailing edges, and so on, which in his view side tracked the main issue. Their experiences so far in the research laboratory suggested that such problems were unlikely to prove critical. In any case they were unlikely to convince themselves further without settling down and attempting to build and develop engines as a whole. The dividend from further research on general lines was likely to be small and they would undoubtedly proceed faster now only by attempting to make the end product. He endorsed gladly Dr. Cohen's injunction to "have a go."

MR. GROOTENHUIS: The advocacy of effusion cooling was both understandable and reasonable at first sight. He must apologise if the paper had given the impression that they had tried effusion cooling once, flicked their fingers at it, and dismissed it from all further consideration. Such was not the case. But perhaps the fact that advances had not been very rapid was indicative of the difficulties associated with effusion cooling.

Nevertheless, perhaps past claims made for effusion cooling, as applied to turbine blades, had been exaggerated. One might certainly achieve good cooling of the metal through which the cooling-air permeated but the "blanketing" effect to heat transferred from the hot gas to the blade surface might not, in practice, be so very significant. In theory it was possible to achieve a reduction in external heat transfer of about 30 per cent by use of effusion cooling if the boundary layer flow were laminar. If, however, the boundary layer flow were turbulent the magnitude of the blanketing effect was questionable. Theory was inadequate and one must judge by experiment. Some experiments that had been made suggested that any reduction of heat transfer was only small and for practical purposes might be ignored. Consider now the probable boundary layer state around a typical turbine blade. On the convex surface a laminar boundary layer might be anticipated over the leading part of the surface to the peak suction point at about mid-chord. From there on

the flow would be turbulent. On the concave surface the state was problematical. The opposing pressure gradients were relatively small and with a smooth steady gas flow one might achieve an extensive area of laminar flow. On the other hand this state could easily be upset by irregularities in the blade profile or, more particularly, by a relatively unsteady and highly turbulent main flow such as occurred within a turbine stage. In practice, therefore, it was improbable that on a typical turbine blade in an engine a laminar boundary layer would be achieved over more than about 25 per cent of the total blade surface, and it was only over this 25 per cent that a substantial blanketing action to external heat transfer would exist. Any overall economy in the required cooling-air quantity accruing from such blanketing action was likely to be small—about 5 to 10 per cent as compared with claims up to 30 to 50 per cent that had sometimes been made.

The main advantage of effusion cooling, therefore, arose not from the blanketing action but from the good internal heat transfer between the cooling air and the porous metal through which it passed. In fact the cooling air might be ejected from the blade at a temperature little less than that of the metal—and one could do no better than that since the heat capacity of the cooling air was then being used with nearly 100 per cent efficiency. At the same time, however, it must be remembered that a good internally cooled blade with spanwise cooling passages could effectively achieve much the same end. In such a blade the cooling air temperature and the blade temperature increased spanwise from root to tip, low metal temperatures being achieved at the root where the stresses were highest. In fact the spanwise blade temperatures approximated to those ideally required for a constant creep strength along a rotor blade span. At the same time, in a good internally cooled blade, the cooling air was discharged eventually from the blade tip at a temperature not greatly different from the *average* temperature of the blade (although it might be substantially less than the tip temperature of the blade). Thus, the heat capacity of the cooling-air was being used effectively with a high efficiency—an efficiency which was little less than could ideally be achieved by effusion cooling.

He contended therefore that in practice the overall advantage in economy of cooling air of an effusion cooled blade over a good internally cooled blade was really little more than marginal. Effusion cooled blades were difficult to make at present. They had made only one so far and the wire mesh from which the porous surface was constructed was far from ideal. A porous surface with a much finer pore size was desirable such that the order of size of any of the minute jets of air leaving the surface were small compared with the boundary layer thickness. In addition one must face troubles due to fouling of the porous material and troubles due to low mechanical strength. In fact it would appear to be the most difficult way one could choose to make a turbine blade. For those reasons he had little enthusiasm at present for effusion cooled blades. At the same time he must emphasise that this was a personal view. The development of such blades would certainly be continued in the belief that long term development might bear a part at least of the fruits suggested by Mr. Grootenhuis.

More important, however, there were other parts of the cooled engine, such as the jet pipe and combustion chamber liners, for which effusion cooling might well prove the ideal. He anticipated that Mr. Grootenhuis might find effusion cooling playing an important part eventually in the cooled engine, even though it might not be incorporated in the blades.

MR. EDWARDS: The question of fouling raised by Mr. Edwards was a popular bogey and one he could answer best by reverting to experience. The air-cooled blades in the experimental turbine at N.G.T.E. had cooling holes of 0·028 in. diameter and this turbine was operated for over 200 hours without being stripped or cleaned. During this period there was no discernible change in the flow versus pressure drop relationship for the cooling passages. This might seem surprising since a film of dirt of, say, one thou. thickness on the passage surfaces would be expected to increase the cooling-air pressure drop appreciably, and the cooling-air was by no means clean. Due to accumulations of dirt, rust, and scale in the piping through which pressurised air was supplied to the rig, some rudimentary cloth filters were placed in the cooling-air supply ducts, but these did not remove fine dirt—as was evidenced by the fine layer of dirt they found deposited on the disc faces, and so on. His belief was that no significant deposit of this dirt took place in the cooling passages due to the molecular forces in a cool gas which tended to drive small particles away from a hot surface. It was a well known phenomena that in a dusty kitchen it was generally the cold water pipes which collected the dirt and not the hot pipes. He believed that this effect had been sufficiently significant to keep them clear of trouble. The implication, therefore, was that filtration of the cooling air might only be desirable if the engine were required to operate in a heavily dust laden atmosphere and only a relatively coarse filter might be necessary even then.

Mr. Edwards might draw comfort from a further point. Passage diameters of about 30 thou. were only likely to arise on relatively small blades of about one inch chord. On larger engines, such as were likely to materialise in practice, the blade chords would be larger and the passage diameters also larger in proportion. It was improbable, therefore, that a necessity for using passage sizes much smaller than about 50 thou. would arise, at least on main aircraft propulsion engines.

The problems of achieving high turbine inlet gas temperatures with small combustion chambers and good temperature distributions were by no means simple and Mr. Edwards pleaded for concessions from the turbine designer. Some concession might, indeed, be necessary, but they must watch that such concessions were not too great. At a flight Mach number of, say 2·5 an increase in engine gas temperature from 1,150°K to 1,400°K would increase the thrust by about 50 per cent Obviously they must not allow the engine weight to

increase simultaneously by a similar amount or they would have no return for their trouble. A poor gas temperature distribution might easily hobble a cooled turbine more than an uncooled turbine if they resorted to the practice of down-rating engine temperature to free themselves of the danger of locally over-heating blades in the vicinity of hot spots. Pre-carburetion of the fuel at the inlet to the combustion chamber might assist in improving the temperature distribution while maintaining high combustion intensity.

An insulating coating around a turbine blade would certainly be most useful if a suitable coating could be developed. A low conductivity ceramic coating might require to be of the order 20 to 30 thou. thickness to achieve a gain of about 100°C in gas temperature and such a coating would then be subjected to a temperature gradient of about 200°C. There was considerable danger of brittle ceramic coatings cracking under such conditions and subsequent flaking off due to oxidation of the metal beneath the coating. It seemed desirable that in such an event the blade should last long enough to see the engine through to its next inspection period. Insulating coatings might best be used, therefore, as a means of extending blade life rather than as a means of substantially raising gas temperatures—until such time as coating of 100 per cent reliability had been developed and proved in service.

It was not easy to give a positive answer to Mr. Edwards' final question. The remarks made in the paper regarding the pros and cons of reheat and high engine temperature were no more than loose generalisations. In practice, as Mr. Edwards hinted, there might be some optimum combination of the two. At the same time, even for a short range interceptor type of aircraft, he believed the optimum would tend to verge towards a high engine temperature with only a small degree of reheat, rather than the reverse, since such an engine might be expected to give a greater margin of thrust over drag at flight speeds and altitudes below the maximum and thus enhance the general manoeuvrability of the aircraft.

DR. MOULT: Dr. Moult had given a very fair account of the effect of raising engine temperatures, with and without reheat, at a flight Mach number of 2·5. As he mentioned in his reply to Mr. Edwards, however, aircraft which flew at Mach 2·5 must also be able to fly and manoeuvre at lower speeds and similar graphs to that shown by Dr. Moult for lower flight speeds might suggest greater advantages for high engine temperatures, particularly when manoeuvrability at the lower speeds was brought into consideration.

One could only agree that much remained to be said on the subject of blade stressing. In many ways an engine with a cooled turbine was almost a new form of engine and it might perhaps be better in some ways to tackle its design with a fresh mind and not strive too hard to achieve the same forms of blading they had become accustomed to in uncooled engines. In high temperature engines, for supersonic flight, factors such as efficiency and blade taper might not have quite the same degree of significance as they had had in the past. There might be a danger of entering a vicious circle in relating stress and temperature in a cooled blade, but he believed that it might not prove too vicious, since, at high metal temperatures, a relatively small drop in metal temperature (and a correspondingly small increase in the degree of cooling) could give a substantial improvement to blade strength. Regarding blade taper, it was a fortunate characteristic of internally air-cooled blades of the type advocated in the paper that blade temperatures were lowest near the root, where the stresses were highest, and for a given mean blade temperature the root temperatures would tend to be lower than they had been accustomed to find on uncooled blades. The weakest part of the blade would tend to occur in the mid-span region. Although these factors by no means eliminated any beneficial effects from taper, he suspected that the benefits of taper might be appreciably reduced when dealing with air-cooled blades.

Dr. Moult's caution was sensible, but in watching the various points he had mentioned they must at the same time watch that they did not attribute a misplaced emphasis to some features they had paid particular attention to in uncooled engines for subsonic flight.

MR. WHITE: It was not explained in the paper that the temperatures shown in Fig. 2 were deduced on the supposition that the basic engine weight (excluding the air intake) per pound of air flow at static sea level conditions would not increase appreciably over current values for uncooled engines. Clearly this assumption became unrealistic at the higher Mach numbers and engine temperatures, where cooling became more difficult and where these difficulties might only be mastered at the expense of extra engine weight. Thus the true values of optimum temperatures might be expected to level off at high Mach numbers when a more realistic assessment became possible. It was impossible, however, to say at the present time what these eventual temperatures might be—only time and experience would show.

In the early phases of development he thought there was little doubt that they would have to be content with the maximum temperatures given by simple air-cooling indicated in Fig. 23. Even these might require fairly extensive development and experience to achieve in practicable and reliable engines. A future phase might logically follow, however, in which some means or other were adopted for refrigerating the cooling air. At flight Mach numbers in excess of 2·0 such a procedure would undoubtedly enable substantial increases in gas temperature to be made. The extent to which such a procedure was employed in practice must inevitably hinge upon the significance of any weight and drag penalty imposed upon the aircraft/engine combination by the particular means chosen for carrying out such refrigeration, and this in turn must depend upon the duty required of the aircraft.

As he had already indicated elsewhere in the discussion he saw little prospect in using ram air directly to cool the blade roots. It might conceivably be used indirectly for reducing the temperature of the

cooling air bled from the compressor or, alternatively, in a system such as that shown in the lower half of Fig. 9.

MR. BLACKWELL: In the preparation of the paper the main emphasis had been laid deliberately upon the means of achieving high temperatures rather than upon the need for them. The means of achievement appeared the more interesting side of the subject since, so far as he was aware, few people challenged the desirability of raising engine temperatures to values at least beyond those that could be achieved for reasonable endurances with uncooled engines (about 1,200°K). Certainly the cooled turbine in the supersonic field bridged the gap between the uncooled unreheated engine and the uncooled fully reheated engine, but it nevertheless appeared to be a relatively big gap. At flight speeds in the vicinity of Mach 1·5 to 2·5, with which they were likely to be preoccupied for a considerable time, he would hesitate to describe an advantage to 15 per cent or more in fuel consumption as marginal. As Mr. Blackwell had implied, it needed more than a few loose generalisations to create a wholly convincing argument —but he doubted if the desirability for the high temperature turbo-jet (with or without the addition of reheat) could be seriously disputed.

He agreed that a strong case for the cooled turbine could be made for the turbo-prop and ducted fan engine. The present applications, however, of such engines were largely civil, and the necessity for extreme and proven reliability was likely to result in their appearance only when experience and confidence had been gained from the prior development of cooled turbo-jet engines for military aircraft. Nevertheless, the development of the high temperature turbo-prop engine must brighten the ultimate prospects of turbo-prop aircraft and it was to be hoped that such development would not be long delayed. It was heartening to hear that Mr. Blackwell had his eyes in that direction.

In the cooled turbo-prop engine the relative significance of turbine efficiency and cooling losses was rather different from that applying to the supersonic turbo-jet. Loss of turbine efficiency due to concessions made for ease of cooling would be less readily acceptable, and the optimum compromise would tend to favour higher turbine efficiency and more modest increases in gas temperature than in the turbo-jet. It was probable that a strong case might be made for liquid cooling (along the lines indicated in Fig. 9) in such applications, although a comparative assessment in detail had yet to be made. Mr. Blackwell was correct, therefore, in his cautious attitude towards radical changes in turbine design if he had the turbo-prop uppermost in mind. Even so, he was certain Mr. Blackwell would find himself driven to make some modifications in blade shape, pitching, etc., if he wanted to achieve the best possible overall performance. The crucial point was that the aerodynamic design of the blading and the design of the cooling system must be tackled simultaneously and not considered as independent problems.

He did not think anyone would dispute the overwhelming importance of the development of manufacturing techniques for cooled blades. It would remain a major preoccupation for a long time to come and would, indeed, demand the closest possible co-operation between the turbine designers, metallurgists, and manufacturing expects.

The Propeller-Turbine in Airline Service

by

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SUMMARY: This paper gives an account of the engineering and operational aspects of the introduction and first three years' operation by British European Airways of the first propeller-turbine engine to go into airline service—the Rolls-Royce Dart which powers the Vickers Viscount air liner. The origin of this type of gas turbine engine and its chief advantages and disadvantages are considered. The main features and operational characteristics of the Dart engine are detailed. The training, operational handling, flight planning and maintenance aspects of the introduction and operation of the Dart engine in the Viscount are reviewed, and the experience accumulated is summarised. It is noted that apart from all the new ground that has had to be covered and all the associated development, no special problems have been encountered. Considerable advantages in respect of engineering and operational simplification have been demonstrated. Experience indicates that this type of engine has good reliability and long overhaul life characteristics, and confirms its general suitability for medium-speed air transportation. The paper ends with mention of some of the probable trends of propeller-turbine development, and with suggestions for some additional improvements which the author considers would benefit civil operators.

1. Introduction

It is roughly three years since a propeller-turbine aircraft began, for the first time in the world, regular passenger operation. The aircraft was the Vickers Viscount, powered by four Rolls-Royce Dart propeller-turbine engines. It went into service with British European Airways (B.E.A.) in April 1953.

Today there is still only this one type actually in civil operation.

This medium-range aircraft has rapidly achieved considerable operational success and therefore also much prominence in this section of the commercial field. Without doubt the propeller-turbine engines have been the major reason for this success, and it is no exaggeration to say that, as a result, this type of engine has already made its mark on civil aviation as being an important advance on the conventional piston engine.

It is therefore considered appropriate that a preliminary review should be made of the main engineering and operational effects of this new type of power unit on airline operations—in spite of it necessarily being limited to refer to one aircraft/engine combination only. The aim of this paper is to make such a review from the engineering standpoint.

The subject has been divided into three parts.

First, by way of brief introduction to this type of engine, its development from the pure jet gas turbine and its most important characteristics are considered.

Secondly, the development of the Dart engine is sketched and its main mechanical and operational features are detailed.

This latter detail will be of assistance to the reader in obtaining a better appreciation of the factors underlying the third and last part, in which the main effects of this type of engine on airline engineering and operations are considered, and the experience gained up to the present time is summarised.

Based on a talk given to the Graduates' and Students' Section on 19th October 1954.

PART I—GENERAL BACKGROUND

2. The Origin of the Propeller-Turbine

With the development of the gas turbine as a prime mover, it was natural that the first aeronautical application of the engine was the pure jet turbine, since this is its simplest, lightest and most readily applicable form. Because of the high jet velocity of this type of engine its propulsive efficiency is good at aircraft speeds of the order of Mach 1, but reduces as flight speed is reduced. For this reason the pure jet was considered too inefficient for medium speed commercial aircraft. The most direct means available for improving this efficiency at medium speeds was to extract most of the energy of the jet, using an additional turbine, and to use the power derived to drive a propeller to obtain the required thrust reaction from a higher mass, lower velocity jet. It was for this purpose that the engine manufacturers went ahead with propeller-turbine designs as soon as the early turbo-jets were under development. Hence the propeller part of the conventional aircraft piston engine came to be married to the gas turbine.

The first turbo-prop to fly in England was the Rolls-Royce Trent, which was a modification of the Derwent engine involving an additional turbine stage plus reduction gear and propeller. Its first flight was in Autumn 1945.

Seven early British propeller-turbine designs were produced and run between 1945 and 1947. Of these the Rolls-Royce Clyde was first to obtain full civil type approval (at 2,500 shaft horse power) but no suitable civil application materialised and so it was abandoned in 1948. Only two have been developed and have gone into production for civil aircraft and only the Dart engine is already in airline service.

The alternative method—the by-pass gas turbine, has been slower in development because of difficulties associated with component matching and gas mixing.

2.1. THE ADVANTAGES OF THE PROPELLER-TURBINE

The propeller-turbine offered an engine with most of the advantages of the pure jet gas turbine, and which, at speeds between 250 and 450 m.p.h., was considerably more efficient. In its simplest form it has the following advantages over the conventional piston engine:—

1. Reduced weight—for a given take-off power the weight is approximately $\frac{2}{3}$ to $\frac{1}{2}$ that of a comparable piston engine, *i.e.* the power/weight ratio is about $1\frac{1}{2}$ to $2\frac{1}{4}$ times that of the best piston engines.
2. Considerably reduced size and frontal area, and hence reduced power plant drag. There are propeller-turbines already in existence with two to three times the power per unit frontal area of the best piston engines.
3. Higher power output—the foreseeable maximum power limit for propeller-turbines is several times that for a piston engine.
4. Continuous combustion—avoiding reliance on spark ignition systems once started.
5. The air flow within the engine can be used to keep all internal metal surfaces at acceptable temperatures and hence no separate external cooling system as distinct from nacelle ventilation is required—a big simplification.
6. No sliding or reciprocating parts, and, in its simplest form, only a single rotating assembly. Hence considerably better mechanical life potential and less critical bearing problems and lubricating oil pressure requirements.
7. Simple, relatively small capacity oil system, with almost negligible consumption, simple temperature control (possibly none) and no deterioration of the oil due to high temperature or to contamination by combustion products.
8. Markedly reduced amplitudes of vibration with consequent improved passenger comfort, and extended life of some components.
9. No "warming up" time limitations, due to absence of critical lubricating and differential expansion conditions. The gas turbine can open up to power immediately from starting provided that the oil temperature is above the minimum required for satisfactory lubrication.
10. The power unit is relatively simple and light, is easy to maintain and has good accessibility, due to the simplicity of the engine and fewer associated control units and accessories.
11. Cheaper fuels can be used, since combustion at constant pressure is less critical on fuel. Kerosine has been used for all civil gas turbines in Great Britain up to the present.
12. Starting can be made automatic since initial combustion conditions are less critical.
13. Special systems for ensuring satisfactory lubrication during starting under cold conditions are not required, since lubrication requirements are less critical.
14. The high windmilling power absorption of the single-shaft propeller-turbine can be used to give increased drag on landing, without resort to the more complicated reverse pitch power braking.
15. Performance and economy improve more with altitude and forward speed.

2.2. DISADVANTAGES OF THE PROPELLER-TURBINE

On the other hand, the simple, single-shaft propeller-turbine, in its present early stage of development, has certain disadvantages compared with the piston engine. These are:—

1. Higher specific consumption—although the reduced fuel costs per gallon, lower drag and weight, and resultant higher speed make the fuel cost per passenger mile more comparable with those of piston-engined aircraft. This disadvantage will be overcome in the future by use of higher compression ratios and turbine materials permitting higher turbine inlet temperatures, leading to specific consumptions better than those of current piston engines.
2. Greater power loss in ambient temperature above the design temperature, due to turbine temperature limitations. Means are available, however, for restoring take-off power to the standard figure under such conditions.
3. Power output has a somewhat greater sensitivity to change of component efficiency. This also has the effect of making the power generating components of turbine engines more amenable to development to greater power output during life. This is due to the characteristics of the propeller-turbine, in which the propeller power is the difference between compressor power absorption and turbine power output, and is only a fraction of these quantities.
4. More power required for starting—the high inertia rotating assembly has to be accelerated up to between one-fifth and two-fifths of its maximum speed before the gas turbine is self-sustaining.
5. Less rapid power response, due to high inertia and high circulating powers. This is a minor consideration for civil operations, since it is no embarrassment provided that the rate of propeller pitch change is matched to the engine acceleration and deceleration characteristics. It can be improved by special control methods if required *e.g.* for naval deck-landing aircraft. Two-shaft (or twin-spool) engines may offer improvements in this direction.
6. More extensive de-icing requirements, due to the increased air flow and intake surface area.
7. The useful power range covers a much smaller fraction of the r.p.m. range than for a piston engine. This tends to raise the propeller noise at cruise conditions and calls for special design action. It also necessitates more accurate control of r.p.m. to maintain required power output.

8. It operates at peak conditions of r.p.m. and temperature for optimum efficiency, and is therefore more susceptible to harm due to any mishandling or malfunctioning which leads to over-heating at the turbine.
9. The high windmilling power absorption makes the "dead" engine case more critical and requires additional propeller safety mechanisms.

PART II—THE DART ENGINE

3. Brief Dart-Viscount Development History

The story of the development of the Viscount between 1945 and 1955 has already been published[1]; so a summary only is given here.

The Dart engine was selected from the three of the seven early designs which were in the 1,000 s.h.p. class, to power Vickers first post-war commercial design. (It will be remembered that the Viking was an adaptation of the military Wellington, and was not a completely new design therefore). This aircraft was, from the outset, a conventional airframe powered by four propeller-turbines. The prototype was known as the Viscount Type 630 and first flew in 1948—the engine having had its first run in 1946. The "630" seated 32 passengers but was assessed to be unsuitable economically in its initial form for B.E.A.'s routes, so Vickers undertook a re-design to meet B.E.A's requirements. This led to the Viscount Type 700 which is now known so well. (Fig. 1).

While this re-design was in progress, valuable development experience was being accumulated on the V.630, including 138 hours regular service flying with B.E.A. between London and Edinburgh, and London and Paris in July and August 1950. Much other engine development work was also going on, in addition to the manufacturer's extensive programme of test bed running. Flying hours were being accumulated by Rolls-Royce on engines fitted in the nose of a Lancaster and in a re-engined Dakota; and by B.E.A. in two such Dakotas (Fig. 2) which were operated for a total of 3,800 engine hours on freight services in Europe.

The prototype Viscount 700 first flew in August 1950 and when it had completed its C. of A. and general tests, it was loaned to B.E.A. for 250 hours route-proving flying in August to November 1952.

Hence, by the time the first of B.E.A.'s Viscounts (Type 701) was put into passenger service in April 1953 there was an extensive background of Dart development running, especially considering the engine had seen no military service. In all, well over 22,000 engine hours had been accumulated, of which approximately 14,000 were flying hours.

Having been projected at the end of the war as a 1,000 s.h.p. engine, the Dart was developing 1,250 s.h.p. in 1948, and 1,400 s.h.p. in 1950. This latter version was designated the Mark 505 for civil application, and was the first Mark to go into service, in 1953. In 1955 a further development, the Dart 506, was introduced into the Viscount 700 series aircraft to replace the Mark 505.

The Dart 506 gives an 8 per cent. increase in cruise power and a 5 per cent. improvement in cruise specific consumption, while maintaining up to International Standard Atmosphere (I.S.A.) +10°C the same sea level powers as the Dart 505 rating at I.S.A., so allowing use of the same reduction gear. This particular development offered a worthwhile improvement in cruise performance and fuel saving at moderate conversion costs.

In addition to 1,400 s.h.p., these two marks give 365 lb. static jet thrust at take-off r.p.m. This is equivalent to an additional 140 s.h.p. (+10 per cent.).

A further development of the basic Dart engine, the Mark 510, has now been type-tested. It has a take-off power rating of 1,600 s.h.p., which represents another 14 per cent. increase on the Marks 505 and 506. This engine will power the first batch of B.E.A.'s Viscount Majors. The Major is a development version of the Viscount 700 series with a 46-inch lengthened fuselage, and is designated the Viscount 800 series. It is due to go into service at the end of 1956.

Yet another Dart variant which Rolls-Royce have under development at present is designated the R.Da.7. This engine is scheduled to give a further increase in cruise power of 15 per cent. initially, and 30 per cent. when fully developed. It will have its take-off power restricted to either 1,700 or 1,800 s.h.p. according to operators' requirements. This engine will be available for a later version of the Viscount Major series, deliveries of which are due to start in 1957.

This power development to about twice the cruise power of the original design during just over 10 years, as shown in Fig. 3, is remarkable. It indicates the development potentialities of the propeller-turbine.

The main performance differences between these four service versions of the Dart engine are shown in Table I.

FIGURE 1. The Viscount 700 (Prototype).

FIGURE 2. One of B.E.A.'s two Dart-engined Dakotas.

TABLE I

COMPARATIVE DATA OF DART ENGINE SERIES

	In Service		*Under Development*	
Dart Civil Mark Number	505	506	510	—
Manufacturer's Designation	R.Da.3		R.Da.6	R.Da.7
Powers B.E.A. Viscount:—	Type 701		Type 802	Type 806
First Year of Service	1953	1955	SCHEDULED FOR 1956	1957
Take-off Data (At I.S.A. Sea Level, Static)				DERATED FOR TAKE-OFF
Shaft Horse Power	1,400		1,600	1,700
Jet Thrust (lb.)	365		370	495
Equivalent Shaft Horse Power	1,540		1,740	1,890
Maintained up to:—	I.S.A.	I.S.A. + 10°C	I.S.A.	Above I.S.A.
R.P.M.	14,500			15,000
Air Mass Flow (lb./sec.)	20			23.5
Pressure Ratio	5·5:1			5·75:1
Power/Weight Ratio s.h.p.:—	1·34		1·44	1·42
Power/Weight Ratio e.s.h.p.:—	1·48		1·57	1·57
Specific Fuel Consumption lb./hr./s.h.p.:—	0·83	0·80	0·75	0·78
Specific Fuel Consumption lb./hr./e.s.h.p.:—	0·75	0·73	0·69	0·7
Cruise Data (At I.S.A. 20,000 ft., 300 knots)				
R.P.M.	13,600			14,000
Shaft Horse Power	850	915	945	1,227
Equivalent Shaft Horse Power	890	955	985	1,325
Specific Fuel Consumption lb./hr./s.h.p.:—	0·71	0·68	0·66	0·62
Specific Fuel Consumption lb./hr./e.s.h.p.:—	0·68	0·655	0·635	0·57

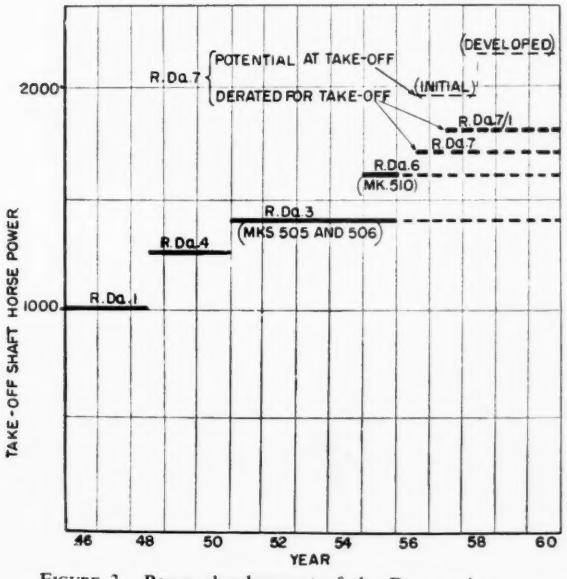


FIGURE 3. Power development of the Dart engine.

4. The Main Features of the Dart Engine

The Dart 506 engine now in service is basically a single-shaft, two-stage centrifugal compressor, axial flow turbine, engine (*see* Figs. 4 and 5). It has seven straight flow combustion chambers employing atomising burners, and it drives a 10 ft. diameter propeller via a reduction gear of ratio approximately one tenth to one. At take-off power, the engine operates at 14,500 r.p.m. with an air mass flow of 20 lb./sec. at a pressure ratio of 5·5 to 1. Neglecting jet thrust, it has a take-off power/dry weight ratio of 1·35 s.h.p./lb. and a specific consumption at take-off of 0·80 lb./s.h.p./hr.

In addition to these main features, the basic Dart engine has several other features worthy of note:—

(*a*) The fuel and r.p.m. controls are inter-connected to give single lever power control. This feature is dictated by the need to satisfy two conflicting requirements of this type of engine. The first is optimum efficiency over the power range, which demands the maximum permissible turbine inlet temperature. The second is the restriction of turbine inlet temperature according to creep life limitations of the turbine

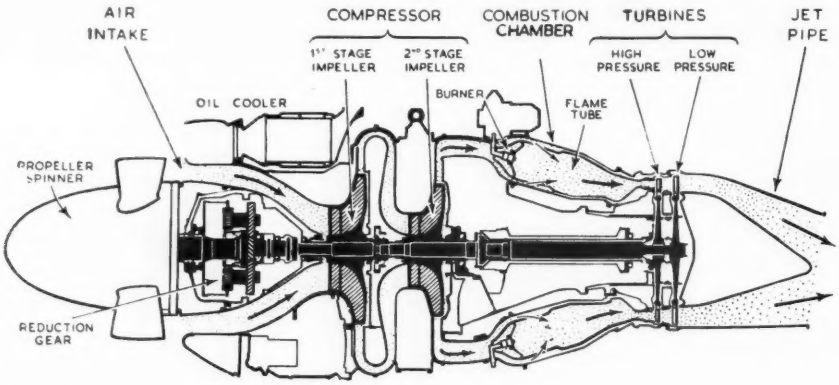


FIGURE 4. The Dart 505/506 engine (cross section).

blading. This inter-connection caters for standard sea level conditions. International Standard Atmosphere altitude conditions are catered for by barometric capsule control which reduces fuel flow according to the intake total pressure, so as to give optimum turbine inlet temperature under I.S.A. conditions corresponding to this intake pressure. In addition it is necessary to cater for ambient conditions warmer than standard, since at constant r.p.m. and fuel flow, the turbine inlet temperature increases about 4°C for each 1°C rise of ambient temperature. A manual fuel "trimming" control is therefore provided for reducing fuel flow relative to r.p.m. to maintain constant turbine inlet temperature under such conditions. No fuel flow correction is made below standard conditions.

(*b*) It has an hydraulic torquemeter system which measures the axial thrust on the three reduction gear layshafts. This thrust is directly proportional to the torque transmitted by the helical high speed train. The hydraulic pressure acts also as a thrust balancing system for the layshafts.

Although neat in conception and of considerable operational importance as an indication of engine performance and of any malfunctioning,

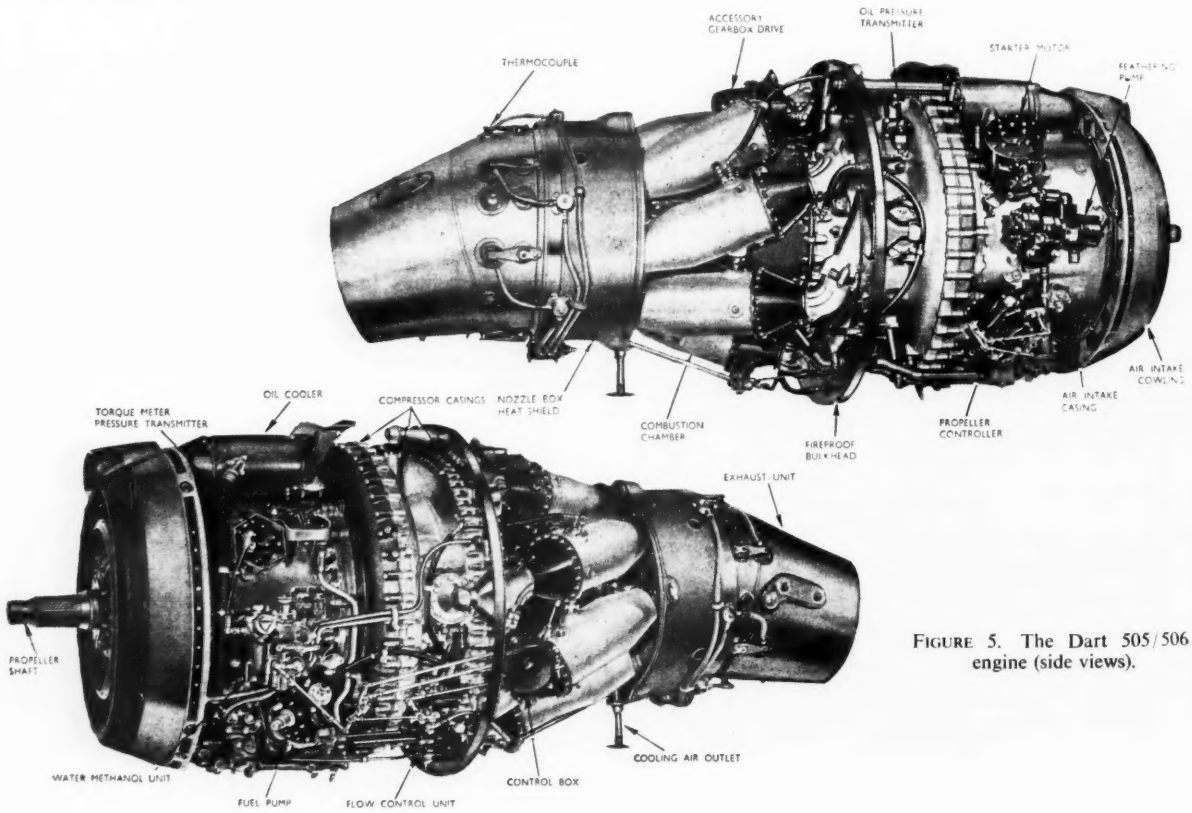


FIGURE 5. The Dart 505/506 engine (side views).

this torque measuring system is not used for accurate determination of power, *i.e.* for tuning.

(*c*) It has an integral oil tank around the air intake, and an oil cooler mounted directly to the engine on top of the intake, so that each engine includes its own complete oil system.

(*d*) It has an automatically controlled power restoration system, which allows nominal take-off power to be retained at all temperatures up to I.S.A. + 30°C, in spite of turbine inlet temperature limitations. The system, when selected, injects water-methanol at take-off r.p.m., thereby decreasing the charge temperature and increasing both the heat input and the mass flow. It operates from the torquemeter signal to restore torque to a pre-set figure corresponding to the nominal I.S.A. power, *i.e.* 1,400 s.h.p. at take-off r.p.m. at sea level.

Due to its basic simplicity as an engine, the number of engine ancillary units and systems is small, and this has resulted in an extremely simple power unit assembly. The complete unit is mounted forward of the wing leading edge, and being of small diameter with centre lines of both inboard and outboard units between 6 and 7 feet from the ground, much of the day-to-day maintenance and also any control checking and setting can be done directly from the ground.

The manufacturer's wisdom of retaining a simple basic design for their first production engine of its kind has been demonstrated by the robustness and reliability of the engine throughout its life. The choice of the centrifugal compressor, backed by the company's successful two-stage supercharger designs for piston engines, has avoided surge and stall problems of the axial compressor with consequent simplification of the engine control system and general operation; it has no doubt contributed considerably to the engine's rapid and successful development.

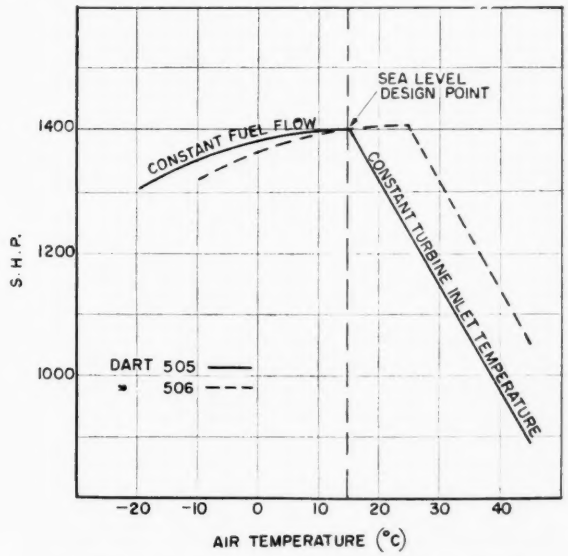


FIGURE 6. Effect of ambient temperature on power (at sea level).

5. The Operation of the Engine

5.1. BASIC CONTROL

The basic Dart engine was designed for I.S.A. conditions, *i.e.* it operates at optimum turbine inlet temperature and hence optimum power output under such conditions. The inter-connection of r.p.m. and fuel flow controls is therefore set to satisfy this optimum condition on a standard day. Hence primary control of the engine is achieved by selection of the r.p.m. to give the desired power.

When conditions are colder than standard the same fuel flow is maintained and so the turbine inlet temperature falls below the optimum. The power at any particular r.p.m. remains substantially constant—falling off only slightly, due to the increased air density (*see* Fig. 6). Under these conditions aircraft take-off power requirement is also reduced.

When temperatures are warmer than standard, it is necessary to reduce the fuel flow to avoid over-heating the turbine. This results in a loss of just over one per cent of take-off s.h.p. for each 1°C increase of ambient temperature.

The variation of shaft power on the Dart 505 engine at sea level at take-off r.p.m. due to change of ambient temperature is shown in Fig. 6. Similar variation occurs at other r.p.m. and altitudes.

Hence although control of r.p.m. is the only form of power control required in ambient conditions colder than standard, in temperatures above I.S.A. secondary control of turbine inlet temperature is also required. The latter is achieved by controlling fuel flow on the fuel trimmer to maintain stipulated exhaust gas temperatures (better known as jet pipe temperatures or J.P.T.'s) dependent on r.p.m. and ambient conditions (*see* Table II). These J.P.T. limits are in turn based on maintaining constant turbine inlet temperature. They are different for the three operational r.p.m. settings—take-off, maximum continuous, and climb and cruise. However, in normal flight, the climb and cruise limit is the only one used directly by the pilot, as the take-off J.P.T. is set by a special procedure which is described later, and maximum continuous r.p.m. is used only in emergency conditions.

These comments on the basic Dart engine apply only to those having I.S.A. conditions as the design point, *i.e.* the Dart 505 and 510. The Dart 506 is different in that due to reduction gear stress considerations it has its maximum fuel flow arbitrarily limited to a value below that which would give optimum output of the power-generating section of the engine at sea level. It is virtually a derated engine at I.S.A. sea level conditions, while giving optimum output at altitudes of 20,000 ft. and above. This sea level fuel limitation results in turbine inlet temperature below the thermodynamic optimum on a standard day, and hence fuel trimming is not required until temperatures are well above standard —until I.S.A. + 10°C in fact. This effect is also shown in Fig. 6.

5.2. PRACTICAL OPERATION

As already mentioned, the throttle lever selects r.p.m.

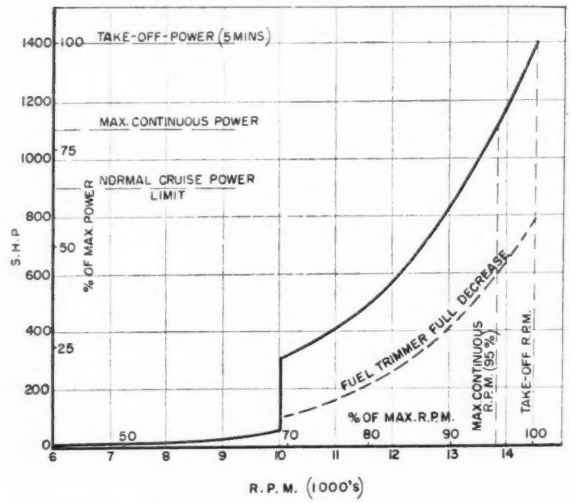


FIGURE 7. Dart 505/506 power characteristics (sea level, static).

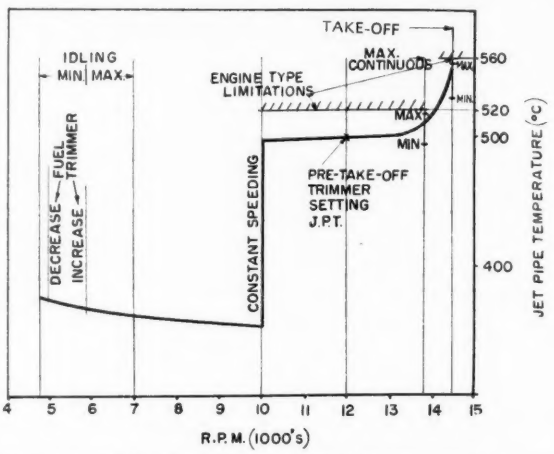


FIGURE 8. Typical Dart 506 r.p.m.-J.P.T. inter-connection curve.

and fuel flow simultaneously, and the inter-connection of these two variables therefore determines the power characteristic of the engine, which is as shown in Fig. 7. By determining the J.P.T.'s at which each particular engine gives acceptable powers at standard conditions on the test-bed, the two parameters r.p.m. and J.P.T. can be used to define the power output. The engine is therefore inter-connected to give specified J.P.T.'s at standard atmospheric conditions at the two setting r.p.m.—maximum continuous, and take-off (*see* Fig. 8). Over the remainder of the r.p.m. range generalised J.P.T. limits are used.

In practice the torquemeter is used only to give a qualitative indication of power for normal running. Its use quantitatively, by pilots, is necessary however when operating in ambient temperatures below those corresponding to limiting J.P.T.'s, since J.P.T. then gives no direct indication of power, unless corrected. For practical reasons, only ground engineers are required to make such corrections. When water-methanol is used for take-off, the torquemeter must again be used for checking power as the power restoration is controlled by the torque signal and because there is no definite relation between J.P.T. and power under these conditions.

The use of J.P.T., in conjunction with r.p.m., as the parameter for assessing and controlling power, has necessitated the use of correction charts by both pilots and engineers, plus special procedures which will be mentioned later. A parameter uniquely related to power would be very much preferred.

The engineers have to check engine powers, as well as comply with engine temperature limitations, and so they require J.P.T. corrections both for power and turbine inlet temperature determination. However, on the basis that the engine's maximum power is limited by the maximum fuel stop as set during control inter-connection, it is necessary for the pilot to contend with turbine inlet temperature limitations only. His J.P.T. corrections are accordingly simplified. This is a particularly important simplification, since although the turbine inlet temperature limitations are common to all engines, the test-bed J.P.T. limits defining engine powers differ somewhat between engines, due to the cumulative effect of production tolerances and deterioration, during successive overhaul lives, on component efficiencies and hence on overall thermodynamic efficiency. It would not be practical for pilots to observe these differences in flight. These small differences of J.P.T.-power relationship between engines make it doubly desirable for pilots to have a control parameter uniquely related to power at any required r.p.m.—such as torque.

PART III—CIVIL OPERATIONS

6. Preparation for Civil Operations

The introduction of such a radically new type of power plant into airline service obviously called for investigation into, and development of, much that was new in the way of procedures for flight planning, for operational handling and especially for maintenance. Following all the early work of formulating requirements, specifying equipment and general liaison with the manufacturers during the design, building and flight test stages, this was the development stage for which B.E.A. assumed the main responsibility.

The flight planning procedures were based largely on known engine and aircraft performance data, substantiated by practical tests, especially for the determination of descent techniques, optimum climb speeds, and in establishing a basis for selection of optimum cruise altitude. The operational handling procedures were dictated more by the type of power plant and much investigation was required to evolve the simplest drills. The 200 hour route proving flying was particularly useful in this respect. The drills finally evolved are covered in more detail later in this paper.

Next to engine mechanical development, the development of maintenance procedures has absorbed most effort from the engine manufacturer and the operators. This was largely a matter of adapting the

methods used during development to suit airline requirements. This involved the simplification and formulation of maintenance drills so as to be usable by less specialised engineers working without the special, often expensive, experimental equipment available during development, and the preparation of a maintenance cycle to ensure the required standard of performance and reliability of all components in service.

In particular, simple procedures for engine tuning and checking, when installed, have had to be developed. These drills are still being improved and simplified, and are dealt with in more detail later.

A large training programme also had to be undertaken. This consisted of two main parts—flying training and engineering training.

The pilots' training programme included the additional amount of technical instruction necessary to give a good understanding of the new type of engine and its functioning, and some additional flying training to cater for the conversion from piston-engined aircraft. No difficulties of conversion became apparent.

The engineers' training was not so much a matter of conversion as of extension to cover the new type of engine, since B.E.A.'s engineers and inspectors do not specialise by aircraft types. Much new technical instruction, requiring an understanding of the principles of the gas turbine, the acquisition of a new vocabulary and a higher all-round standard of training and experience was required. This latter point will be best appreciated by reference to the engine tuning procedure discussed later.

7. Operational Handling

The high idling and taxying fuel consumption (idling consumption is about 40 per cent. and taxying consumption is 60-70 per cent. of cruise consumption) make it important to reduce to a minimum engine running time before take-off. For this reason and the fact that engines can be opened up to take-off power safely, without previous checking, a special air traffic control procedure has been in use to enable captains to obtain their take-off clearance before starting engines. Once given this clearance, the aircraft receives priority for take-off on reaching the runway.

Apart from this aspect, the general handling does not differ radically from that for a piston-engined aircraft. The main points of difference are as follows:

7.1. ENGINE STARTING

Engine starting is automatically controlled, and is therefore not susceptible to technique such as results when manual operation or control is required as in the case of priming a piston engine. Since the start of operations, starting reliability has been improved by the introduction of "high energy" ignition to replace the original "torch" ignition system.

7.2. TAXYING

Taxying is done as far as possible at fixed throttle settings using nose wheel steering and brakes for control. This is found to be best because of engine characteristics. All four engines are started up on the apron before taxying, in order to use the ground starting equipment, otherwise taxying out could be done on two engines (as is the practice for taxying-in after flight), but the resulting economy of time and fuel would be slight.

7.3. TAKE-OFF

The propeller-turbine does not need any warming up, nor any ignition check, before take-off. Hence pre-take-off checks are very brief. When operating the Dart 506 engine in ambient temperatures below I.S.A. + 10°C no fuel trimming is required for take-off, and hence there is only a cursory oil pressure check at 12,000 r.p.m. (43 per cent. power condition) plus general precautionary checks of instruments and controls, before slipping brakes and opening up to full power. When operating at ambient temperatures warmer than this it is necessary to trim off fuel to prevent the turbine inlet temperature exceeding limitations. The procedure in use so far requires a specified J.P.T. to be set up at 12,000 r.p.m. This J.P.T. is determined for each engine according to its r.p.m.-J.P.T. inter-connection (*see* Fig. 8) and is such as to ensure that correct conditions will be obtained at take-off r.p.m., so avoiding the necessity of opening up to take-off power against the brakes. This procedure has the two disadvantages of the use of J.P.T. as the basic parameter for adjusting fuel flow, and the time required to set four engines accurately to a stabilised figure. Hence from the start of operations a method has been sought to enable direct pre-selection of fuel flow (and hence of both power and J.P.T.) to be made according to the ambient temperature. This operational improvement is now attainable and such a procedure is being introduced for the Dart 506 and 510 engines. In the future, automatic jet pipe temperature control may be fitted to take care of this requirement.

7.4. CLIMB AND CRUISE

For all except the shortest route sectors, constant climb and cruise r.p.m. is used and the only power control required by the pilot, apart from synchronising r.p.m., is that of monitoring the J.P.T. at its limiting value when operating in warm temperature conditions.

With the Dart 505 when climbing through a standard lapse rate atmosphere, with a standard barometric control in the fuel system, no additional trimming (once the initial setting has been made) should be necessary. It will be appreciated that the existence of these two conditions simultaneously is the exception rather than the rule, and, especially when temperature inversions are met, repeated checking of J.P.T. is necessary if O.A.T. (Outside Air Temperature) is above standard.

The position is rather different with the Dart 506 since the fuel system altitude characteristic is not based on standard atmosphere conditions as with Darts 505 and 510. The barometric capsule under-corrects with increase of altitude to raise the turbine inlet temperature above that to which the engine is set at sea level (as referred to in Section 5.1) up to the optimum value at 20,000 ft. and above. Hence additional fuel trimming

is necessary during climb in temperatures well above I.S.A., even if the temperature lapse rate is standard.

7.5. DESCENT

Descent at flight idling r.p.m. at low power is straightforward, but before the final approach it is necessary to adjust the fuel trim and, according to the ambient temperature, to select water-methanol power restoration so that, should an over-shoot become necessary, sufficient power will be available without over-heating the turbines.

7.6. LANDING

Landing is conventional, except that there is a tendency to "float"—that is, there is a more gradual loss of height than with a piston-engined aircraft as throttles are finally closed, due to the thrust characteristics of the engine discussed earlier. Also, to obtain maximum windmilling drag during the landing run it is necessary to put the aircraft firmly on the runway immediately after touchdown so as to bring the propellers on to the ground fine pitch, as this is controlled by undercarriage microswitches.

7.7. BAULKED LANDING

Baulked landing (or overshoot) technique differs only in that thrust response to throttle movement is rather slower than with piston engines. Hence decision to overshoot must be made rather earlier with this aircraft. In addition, rapid throttle opening is to be avoided. This is because the reduced engine acceleration (due to the characteristics of this type of engine and to the amount of energy required to accelerate the rotating assembly) causes the increase of air flow to lag behind the increase of fuel flow. This lag increases as the rate of throttle movement increases and the result is an excessive increase of fuel-to-air ratio and excessive turbine inlet temperature.

The acceleration characteristics of the engine worsen somewhat as r.p.m. is reduced, and so it is especially important not to attempt to open up rapidly from low r.p.m., such as ground idling r.p.m.; but this extreme case applies to ground handling only, of course.

This over-heating of the turbine, either due to rapid throttle movement or to over-fuelling under high ambient temperature conditions, and the almost opposite effect of over-rapid cooling causing excessive thermal shock, due to rapid shutting down which is even more serious, are the only two harmful effects on the engine for the prevention of which special handling instruction is required.

7.8. TURBINE INLET TEMPERATURE LIMITATION

Turbine inlet temperature limitation in flight is, as stated earlier, achieved by manual control of jet pipe temperature. For constant turbine inlet temperature, the J.P.T., being measured aft of the turbine, increases slightly with increase of ambient temperature and pressure. Hence at the start of Viscount operations pilots were required to make small corrections to the J.P.T. limit according to altitude as shown in Table II*a*. J.P.T. corrections were also required for ambient temperatures above standard. The type of correction chart which was issued to pilots initially for determination of J.P.T. limits at each of the three r.p.m. ranges is shown in Fig. 9(*a*). It will be noticed that instead of quoting ambient temperature, the charts are based on the aircraft O.A.T. gauge reading, which incorporates a mean ram temperature rise correction as a simplification for pilots.

During investigation into the operational range of climb and cruise conditions over which altitude and temperature corrections to J.P.T. applied, it was found that the pressure altitude correction was covered by the ambient temperature correction to within the normal accuracy of J.P.T. control. Hence a much simpler linear correction chart of cruise J.P.T. versus O.A.T. gauge reading was introduced. Following from this it was found to be practical to simplify all J.P.T. corrections in this way. Table II(*b*) shows the revised form of the " Operating Limitations," and Fig. 9(*b*) shows the simplified chart.

As a result of careful investigation into the general operating experience gained with this engine and of a study of the performance relationships and requirements, it is now considered satisfactory to accept small changes in turbine inlet temperature and hence simplify J.P.T. limitations a further stage—in fact to delete the corrections entirely and to operate to a constant J.P.T. limit for each of the three operational r.p.m. settings under all ambient conditions. The " Operating Limitations " can be simplified as shown in Table II(*c*) and pilots' correction charts could therefore be discarded entirely.

Speaking generally, the handling of this engine is remarkably simple once its basic characteristics are fully appreciated. Once pilots have flown with these engines they realise their virtues.

8. Flight Planning Procedures

At the start of operations, the recommended climb and cruise r.p.m. was 13,300, and flight planning was based on cruising at the maximum practicable altitude to achieve maximum fuel economy. For handling reasons, the altitude selected was that up to which a rate of climb of at least 200 ft./min. could be maintained at maximum take-off weight. This gave a cruise altitude of 19,000 ft. at I.S.A. conditions and maximum weight. The climb was done at the gradient giving the maximum air miles per gallon of fuel required to reach cruise height.

Subsequently, in April 1954, 13,600 r.p.m. was cleared for climb and cruise, giving improved fuel economy and sector times. However, the introduction of the Viscount on some of B.E.A.'s shorter routes (between 60 and 200 nautical miles) on which it was not practical to climb to the normal cruise altitude, necessitated the use of altitudes lower than the optimum, and which, at 13,600 r.p.m. (or lower r.p.m. to cater for the aircraft speed limit, where necessary), would have resulted in increased cruise powers being used. The altitudes selected on these routes were

TABLE II

DART 505/506 ENGINE OPERATING LIMITATIONS—SHOWING STAGES OF SIMPLIFICATION

(*a*) ORIGINAL TABLE

Engine Condition	*r.p.m.*	*Max. J.P.T. in I.S.A. Conditions (°C)*			
		Pressure Altitude (ft.)			
		S.L.	10,000	20,000	30,000
Climb and Cruise	Below 13,800	555	545	535	525
Maximum Continuous	13,800	555	550	545	535
Take-off (5 mins. max.)	14,500	595	590	—	—
Ground Idling	4,750 to 7,000	500	—	—	—
Starting	—	640	—	—	—

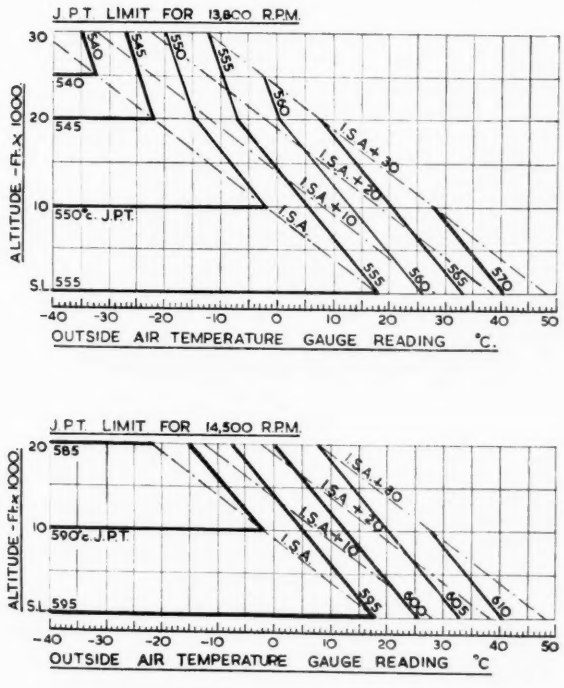
(*b*) REVISED TABLE (J.P.T. LIMIT BASED ON O.A.T.)

Engine Condition	*r.p.m.*	*Maximum J.P.T. (°C)*					
		Ambient Temperature (°C)					
		−45	−25	−5	+15	+35	+45
Climb and Cruise	Below 13,800	520	530	540	550	560	565
Maximum Continuous	13,800	540	545	550	555	560	563
Take-off (5 mins. max.)	14,500	—	585	590	595	600	603
Ground Idling	4,750 to 7,000	500					
Starting	—	640					

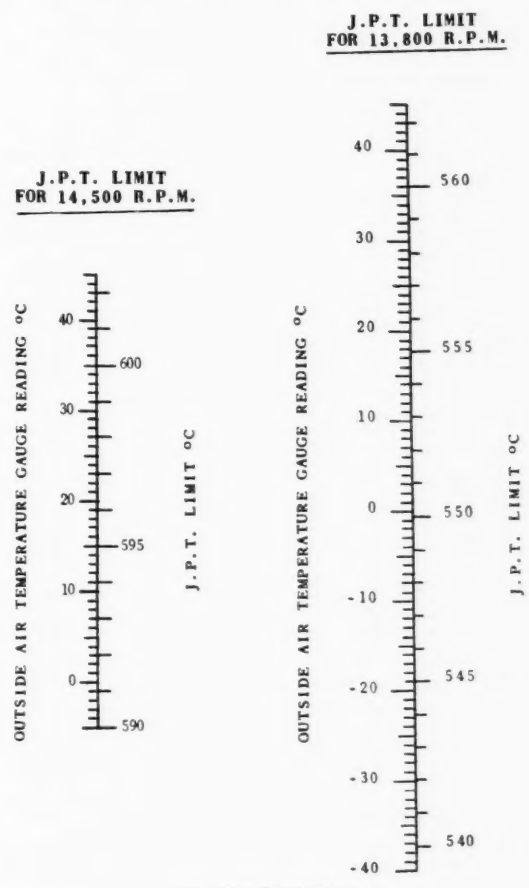
(*c*) PROPOSED TABLE (CONSTANT J.P.T. LIMITS)

Engine Condition	*r.p.m.*	*Max. J.P.T. (°C)*
Climb and Cruise	Below 13,800	(To be declared)
Maximum Continuous	13,800	555
Take-off (5 mins. max.)	14,500	595
Ground Idling	4,750 to 7,000	500
Starting	—	640

FIGURE 9 (*below*). Operating J.P.T. Limitations Charts.



(*a*) Original Chart.



(*b*) Simplified Chart.

based on striking a mean between reducing the sector times by reducing altitude, with consequent reduction of direct operating costs, and the corresponding increase of fuel costs. At the same time, the r.p.m. used on these short sectors was reduced to 13,000 for cruise to restrict the shaft power to not more than a nominal of 870 s.h.p. (62 per cent. of take-off power) which the manufacturers considered was the maximum cruise power consistent with long overhaul life at that stage of development of the Dart 505 engine.

With the introduction of the Dart 506, this shaft-power limitation was raised to 900 s.h.p. (64 per cent. of take-off power). At the same time the cruise r.p.m. for the shorter sectors was subdivided into three groups—13,300, 13,000 and 12,500 r.p.m. according to the optimum altitude for the particular sector length. This was done to enable cruise powers to be kept as close to the 900 s.h.p. limit as practical.

The overall effect of these increases in cruise r.p.m. and cruise power when operating at the optimum 200 ft./min. climb altitude, has been to increase the cruise speed of the aircraft by about 30 knots and improve the specific air range by about 22 per cent. When considering operating at a set altitude, the effect has been an increase of about 40 knots in cruise speed, with negligible improvement in specific air range.

At the start of operations, water-methanol was scheduled for use when the take-off requirements could not be met by " dry " take-off performance. It has now been made standard practice to select water-methanol for all take-offs in temperatures above standard since it will not normally be injected unless engine power is below the I.S.A. nominal, *i.e.* unless fuel has been " trimmed " off to cater for J.P.T. limitations.

To simplify the procedure for " uplifting " water-methanol, and avoid the need to "off-load" any remaining quantity at some stations where it would not be required for take-off, it has been made a general practice to carry a stated quantity according to the month of the year and the temperatures to be encountered over the route network during that month.

9. Maintenance Procedures

The simplification of maintenance procedures associated with checking and correcting engine performance has been the main operational need, and there is still room for further simplification. Otherwise the general maintenance requirements for mechanical and functional checking do not differ appreciably from those in use on piston engines, except for the deletion of ignition checks, plug changes and boost control checks.

There is no routine maintenance required on the engines while away from base, and servicing is confined to the oil tanks which require topping up only infrequently because of the low consumption rate of about 0·1 pint/engine flying hour.

9.1. ENGINE TUNING SETTING AND CHECKING

This has become known as the " inter-connection procedure," becuse it is so directly associated with the inter-connection of r.p.m. and fuel controls.

The main factors influencing the tuning checking procedure are:—

(*a*) The use of pyrometric instrumentation in conjunction with the engine tachometer, for assessing engine performance. The characteristics of the thermo-couple system are such that accurate calibration of the complete system on each engine is required, to ensure sufficient accuracy of indication—1 per cent. change of J.P.T. is equivalent to approximately 1·5 per cent. change of power.

(*b*) The use of individual J.P.T. limits for each engine to define the acceptable power limits at take-off and maximum continuous r.p.m.

(*c*) The effect on engine power and J.P.T. of ambient conditions and other variables—requiring accurate corrections to be made.

(*d*) The high power index of the engine—a change of 1 per cent. of take-off r.p.m. results in a 4 per cent. change of power output.

The effect of these factors on inter-connection checking is:

(1) To obtain repeatable r.p.m. - J.P.T. relationship at standard sea level ambient conditions, it is necessary to observe stipulated conditions for both oil temperature and stabilisation time.

(2) When ambient conditions are other than standard sea level, some correction of observed J.P.T.'s is necessary. Fig. 10 shows the ground engineers' J.P.T. correction chart as used up to the present. It will be seen that engineers are required to correct for both ambient temperature and pressure. These corrections are based on:—

(*i*) Retaining constant turbine inlet temperature in ambient conditions such that fuel flow has to be " trimmed off " (*i.e.* reduced) to avoid overheating the turbine.
Under these conditions small corrections to J.P.T. according to ambient temperature have been applied up to the present (*see* Fig. 10), but they would be deleted with the introduction of constant J.P.T. limits for general operation, as referred to earlier (Section 7.8).

(*ii*) The J.P.T. resulting from constant maximum fuel flow in ambient conditions such that J.P.T. limitations are not encountered.
In this case a fairly large J.P.T. correction may be required to cater for the J.P.T. - O.A.T. relationship at constant r.p.m. and fuel flow mentioned earlier. This relationship is represented by the slope of the correction lines to the left of Fig. 10.

(3) When ambient conditions are such that fuel flow has to be reduced on the trimmer as in (2) (*i*), it is still necessary to set the maximum throttle stop on the fuel control unit so as to ensure that correct power will be achieved at maximum fuel flow on a standard day and below. This is achieved by stipulating the clearance between the throttle and its maximum stop according to ambient conditions, thus relating the fuel flow reduction below maximum to the existing ambient conditions.

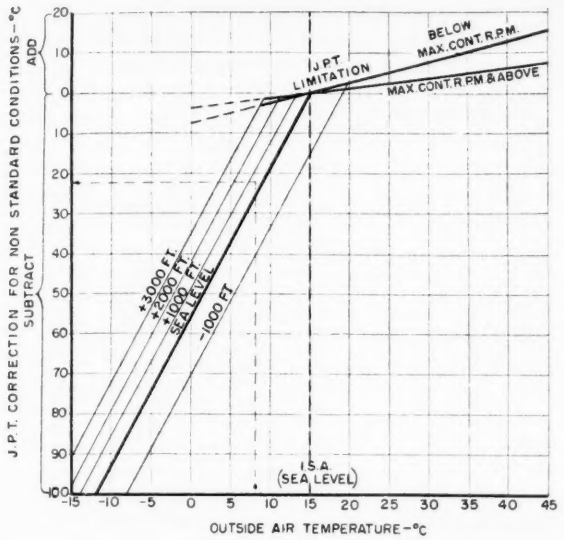


FIGURE 10. Current J.P.T. Correction Chart for engine ground run checks.

Engineers are provided with a second chart as shown in Fig. 11 for determining the required throttle maximum stop clearance both for control settings and for routine engine checks.

(4) During installed life, small changes in the r.p.m.-J.P.T.-power relationships can occur due to:

(*a*) Changes of component efficiency, due to loss of aerodynamic and hence thermodynamic efficiency. This results from contamination or erosion of surfaces, or from thermal distortion of such items as combustion chamber flame tubes.

(*b*) Changes of fuel and propeller control unit characteristics, due to settling of springs, wear, and so on.

It is obviously necessary that any such changes of engine characteristic are detectable during normal engine tuning checks during life, so as to ensure that, should any appreciable change of performance occur, it cannot be overlooked, and that appropriate rectification is made. For example, a high J.P.T. at a given r.p.m. may be due to:—

(*a*) high fuel flow, in which case, if the fuel control unit characteristic is acceptable, a reduction of fuel flow will restore the power to nominal; and/or

(*b*) reduced component efficiencies, in which case reduction of fuel flow will bring the power below nominal.

It will be evident that, on this score, the use of J.P.T. alone as the parameter for checking power is insufficiently determinate. The best way of relating J.P.T. to power is to include a fuel flow measurement, so that after adjusting the inter-connected controls a fuel flow check is made, for comparison with the original inter-connection figure, to verify that the fuel control

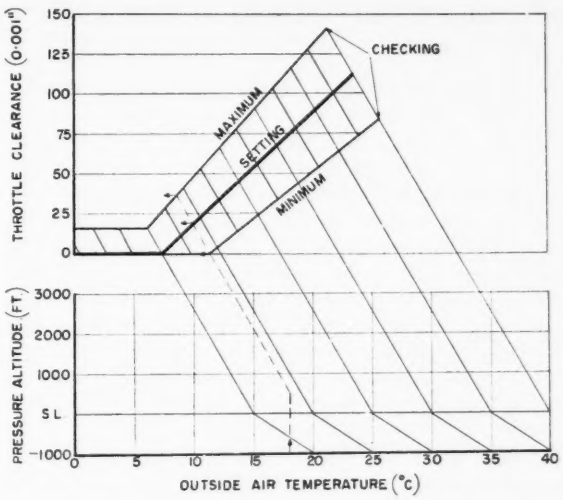


FIGURE 11. Throttle stop Clearance Chart for control interconnection.

unit characteristic has not altered. This procedure has been introduced and is still being developed. Apart from providing a check against power deterioration, it also insures against the effects of any large instrumentation errors.

On the point of change of component efficiency, a few cases of power deterioration have been encountered in service due to contamination of the compressor by oil and dirt drawn in through the intake. Some early propeller seal troubles, which have now been overcome, led to oil getting into the compressor, where it adheres and becomes "coked" in the second stage. This leads to reduced air flow and increased compressor outlet temperature, so that for a given J.P.T. the power is reduced.

To assist in cleansing an engine internally when it is known that a quantity of oil has been inspired sufficiently recently for it not to be too thoroughly "coked" on the compressor, a compressor washing procedure has been introduced. This involves injection into the intake of a quantity of solution composed of water and kerosine, plus a wetting agent, while the engine is running at low power condition. Because of the cost of the equipment this procedure is carried out at Base only, where it has been of some assistance in maintaining satisfactory engine performance.

The effect on the engine's power output of changes of component efficiency can be understood when one remembers that approximately twice the propeller shaft power is in continual circulation between the turbine and the compressor. Hence, any percentage increase of compressor power absorption will have a doubled effect on decrease of shaft power, and any reduction of turbine efficiency will have a trebled effect.

It will be evident even to those who have had no first-hand experience of propeller-turbine engines that they are much more sensitive to ambient conditions than piston engines.

In addition to the routine job of checking engine

performance on the ground, there is, of course, also the altitude case to be considered. R.p.m. selection is unaffected by altitude, so that the engine operates at a higher non-dimensional r.p.m. but, as mentioned earlier, the fuel flow is reduced by action of a barometric capsule, to maintain correct air/fuel ratio. The most likely cause of low engine performance at altitude only is faulty altitude characteristic of the fuel control unit. Fortunately, this can be checked on the ground (using a specially developed rig which is held at Base) by applying a depression, corresponding to the required altitude, to the capsule, and determining the fuel flow compared with the sea level value. Although this does not actually check the engine performance for altitude, it does enable most engine altitude snags to be cleared by ground checking without involving the large expense of test flying the aircraft at altitude to confirm or isolate the snag. The cost of test flying per hour is in the three figure range, and so the value of such ground checking procedures can be appreciated.

If the ground inter-connection and fuel control unit altitude characteristic of an engine are correct, then only irregular combustion conditions can reduce performance at altitude, so that if such a defect persisted it would be necessary to check burners and flame tubes, but no such trouble has been reported in service.

From the foregoing description of the requirements for ensuring correct engine performance, it will be appreciated that much work has been required to ensure that the necessary information, in the form of checking and "trouble-shooting" procedures, correction charts and acceptance standards, has been disseminated in a suitably logical and understandable form to the engineers concerned. It has been necessary to provide Outstation Engineers with suitably modified procedures to cater for the fact that, for reasons of expense, some of the ground equipment required can only be held at Base.

It should be remembered that all these comments refer specifically to the first propeller-turbine to be put into service. While it will be evident that the performance setting and checking operations for this engine still require some improvement from the airline's point of view (in that the tuning operation needs to be simplified to a procedure comparable with the physical job of changing a power unit) it would indeed have been remarkable, although very welcome, if this prototype civil engine, as it might be described, had left no room for improvement. However, the inter-connection problems referred to are by no means fundamental to this type of engine, and some simplification has already been achieved on this particular engine.

Improved accuracy of the primary engine instrumentation would confer considerable benefit on tuning procedures for this engine and the measurement of low pressure turbine inlet temperature, in place of J.P.T., which is under development, should give an improvement.

10. Development in Service

Having started operations in the "Dart Dakota" at 250 hours life between overhauls, the life of the engine had been increased to 400 hours by the time Viscount services started in April 1953. Since then a continuous intensive drive to increase overhaul life has been maintained. This has resulted in all engines being operated to an overhaul life of 1,050 hours since October 1954. This rate of progress gives a good indication of the engine's reliability and life potential.

The importance of continued life development will be appreciated from the fact that in spite of the increases obtained so far, the engine overhaul costs still constitute roughly one third of the total engineering costs of the Viscount. The corresponding figure for a piston-engined aircraft would be about a quarter of the total cost, in spite of its long development. Against this must be set the extra maintenance costs of the piston engine.

It is confidently expected that overhaul lives of this type of engine will ultimately exceed even the best foreseen for piston engines. So far the only items on which it has been necessary to impose a life limitation, such as to restrict the overhaul life development of the complete engine, have been the combustion chamber flame-tubes and the first stage impeller.

When necessary, the flame tubes can be changed during installed life without removing the engine, although B.E.A. finds it worth while to change engines to achieve this so as to reduce the time aircraft are off service to a minimum. The flame tubes are changed in the workshops and the engine is then re-installed elsewhere. The flame tubes in current use are cleared for more than half engine life between overhauls, and a tube suitable for more than the present engine life is now available, so this limitation will be removed shortly. The development problem here is to produce an efficient low-loss tube to withstand the varying thermal and pressure stresses imposed during a thousand or more hours of engine operation, without cracking or excessive distortion.

With the introduction of an improved impeller and the modified flame tubes during 1956, it will be possible to continue engine overhaul life development above the present 1,050 hours towards the next goals of 1,500 and then 2,000 hours.

In parallel with the extension of overhaul life, the normal operating r.p.m. has been raised from 13,300 to 13,600 r.p.m., and the maximum operational cruise power has been raised from 700 to 900 s.h.p., without any major modifications to the engine. This has resulted in the performance and operational benefits mentioned earlier, with corresponding commercial benefits.

This dual development of engine overhaul life and engine performance is but the superficial evidence of all the intensive mechanical development which has been carried on ceaselessly by the combined efforts of the operator and manufacturer since 1951. This development in service covers a multiplicity of tasks, and is always essential in order to achieve good reliability and to reduce operating costs when introducing new equipment[2], especially when introducing a new engine. It has been doubly important in this introduction not only of a new engine but of a new type of engine.

A record of all the mechanical development and maintenance development of the Dart engine during its service life would have to be a long and detailed account to be complete. It would involve statistics of defects, defect rates, premature removal and feathering rates, trials of new equipment and modifications and much other data necessary to record the many sides to such development. This aspect has already been summarised in part of another paper[3] and no attempt has been made to include such a record here.

It will suffice to say that the standard of reliability of this engine achieved already gives no cause for doubting that the propeller-turbine offers a distinct improvement over the piston engine in this respect. Not unexpectedly there have been recurrent defects associated with such items as reduction gear bearings, the torquemeter, turbine bearing and turbine blades, which have necessitated some re-design and modification action, but their extent and number and expense to the airline must be accepted in the cause of progress. The most encouraging feature in connection with reliability is the in-flight failure rate—that is the rate of featherings in flight for engine mechanical defects. This is at present less than 0·05 per 1,000 engine hours. It appears that this may well be one of the characteristics of propeller-turbines, and one of the big advances which this type of engine offers in safety of air travel. Due to the simple bearing requirements of this engine there is less to suffer mechanical breakdown as a result of wear or inadequate lubrication—surely the more common cause of piston engine failures. Even if an incipient mechanical failure (other than a fatigue failure) exists, this will normally take longer to develop, so that routine oil filter inspections at a suitable frequency will show up such failures before they develop to the stage of mechanical breakdown sufficient to prevent an engine functioning satisfactorily.

11. Operational Experience

At the start of 1956 there was a total of over three quarters of a million engine hours of service flying to the credit of the Dart engine. Of this total over one-third million hours have been flown by B.E.A. Considering that the engine has had no military service, this constitutes an extensive background of experience on which to assess the operational success of this engine.

As this paper is intended to cover only the operational effect of this engine on airline engineering, no assessment of the economic and commercial results of the operation of the Viscount has been attempted. It has been the subject of another recent paper[1].

From the engineering standpoint the Viscount has retained a very satisfactory reputation with passengers for reliability and punctuality. This means a great deal to an airline, and it is in no small way due to the reliability and simplicity of this type of power plant, and the reduction of petty unserviceability which results, that this reputation has been maintained. Add to this the obvious passenger appeal of flight in this type of four-engined aircraft due to the reduced noise and vibration levels in the cabin (resulting in a marked reduction—one might almost say deletion—of human fatigue) and due to its ability to fly "above the weather" on all normal occasions. It will then be understood why the Viscount has become so popular with the air travelling public.

Leaving airline economics aside, it is evident that the propeller-turbine is making the engineer's job more simple at the same time as it makes passenger travel more comfortable.

12. Looking to the Future

In view of the early success and the obvious advantages of this type of prime mover, its use in a large proportion of medium-range commercial transport aircraft in the near future seems assured. The new engines of the next decade will bear many new features resulting from normal progress and development and will undoubtedly embody the experience gained with the Dart engine. In the interests of fuel economy, operational flexibility and general refinement for their particular roles, future propeller-turbines will undoubtedly, although unfortunately from the first cost and maintenance point of view, become more complex. The following are likely to be the main differences:—

(*a*) Axial compressors will be in general use to give increased pressure ratios and efficiencies, leading to improved economy. This may necessitate slightly more complex control systems to cater for the more critical characteristics of this type of compressor. Mechanisms between fuel and r.p.m. selection controls to give optimum power response characteristics, and other refinements such as variable compressor inlet guide vanes and compressor bleed valves may be required.

(*b*) Automatic ambient temperature compensation and automatic turbine inlet temperature limitation will probably be included in the fuel control system.

(*c*) Cooling of turbine blades and nozzle guide vanes to enable higher operating temperatures to be used in association with increased pressure ratios, for improved economy without reducing blade life.

(*d*) Compounded (or two-spool) gas turbines are being developed to give improved flexibility and flatter efficiency characteristics.

It is the author's view that the airline operator would also benefit considerably from other improvements, such as:—

(*a*) The design of fuel systems requiring much less fine filtration standards than at present, leading to reduced operating costs, due to cheaper fuel, less risk of contamination of fuel systems, less fuel system maintenance, less operational delays and some reduction of the fuel icing problem.

(*b*) Use of engine heat for de-icing purposes whereever possible, (provided operating economy is not sacrificed)—giving a more reliable system requiring less maintenance.

(*c*) Use of compressor bleed for cabin pressurisation to avoid separate cabin blowers and their

drives, provided adequate precautions can be taken against contamination of the cabin air.

(*d*) Improved accuracy and readability of instrumentation, especially in respect of direct power indication. Either an accurate powermeter or torquemeter is required.

(*e*) Performance to allow take-off power to be maintained over the whole operating temperature range without resort to means of power restoration, and to allow flight "above the weather" to be maintained irrespective of ambient temperature. With the higher cruising speeds and altitudes foreseen, both of these improvements should be obtainable since the resulting sea level potential power output may not be required for take-off.

(*f*) Design of engine controls with special reference to:—

(*i*) sensitivity of adjustment to assist maintenance engineers during engine tuning. One turn of a stop should not have more than a one per cent. effect on power, it is suggested.

(*ii*) avoidance of secondary effects on engine performance and control inter-connection due to thermal expansion and oil temperature.

(*iii*) maximum simplification of control inter-connection, especially so that inter-connection of controls over the power range is not affected by secondary adjustments such as may be required at the idling r.p.m. condition.

(*g*) A considerable reduction in engine noise, plus special consideration by the aircraft, engine and propeller manufacturers at the design stage to keep cabin noise level as low as practicable.

(*h*) Avoidance of the use of expensive lubricating oils.

(*i*) A lightweight starter system independent of ground equipment.

13. Conclusion

The evidence of the past three years' successful and profitable operation of the Viscount with its Dart engines leaves no room for doubt that, even at this stage of its development, this type of engine is a better prime mover, both mechanically and operationally, than the piston engine, for medium-range transport aircraft. It offers simplified maintenance and improved passenger comfort. It promises better reliability and improved engine life.

These benefits are obtained without prejudice to any aspect of commercial operation, since it has been proved that aircraft so powered can operate normally and without restriction even in the most congested traffic areas. They can also be maintained alongside their piston-engined counterparts without necessitating any appreciable changes in normal maintenance policy or procedures.

B.E.A., among others, is now reaping the rewards from backing this new engine type in its early days and from all the development effort which the Corporation has applied during its introductory stages.

In attempting to cover, from the point of view of an airline engineer, the background and operational development of the propeller-turbine up to the stage of its acceptance as a proven and economically desirable form of prime mover, many aspects have received inadequate recognition—in particular the continuous development, effort and co-operation of Rolls-Royce, Vickers-Armstrongs and other companies throughout the story. There is a warm appreciation within B.E.A. of the vital part which Rolls-Royce, in particular, and Vickers-Armstrongs have played. It has been an impressive story of co-operation between the three parties. Great pride is felt that B.E.A. has formed the instrument through which the enterprise of these two companies has come to fruition, and has thus been primarily instrumental in the successful development of the world's first propeller-turbine aircraft into one that is destined to form the backbone of several of the world's short and medium-haul air fleets.

Although the future application of the propeller-turbine to a large proportion of short and medium-range transport aircraft seems assured, the future trend for the longer range aircraft cannot yet be forecast with such certainty. The relative merits of the pure jet and the propeller-turbine for this application have still to be evaluated in practice. An interesting competition between these two types of prime mover is about to start. The next decade should indicate whether, and to what extent, the propeller-turbine is the more suitable for this application also, although it is not expected to be competitive for very high speed travel.

Whatever the outcome, there are propeller-turbines coming into service and under development which will give good account of themselves during this next testing period.

ACKNOWLEDGMENT

The third part of this paper covers some of the operational development work with which it has been the author's privilege to be directly associated since 1951, under the leadership of R. M. Cracknell (B.E.A.'s Engine Development Manager). The author wishes to express his thanks both to British European Airways for permission to present this paper, and to Mr. Cracknell for his advice and support in preparing it. The views expressed throughout are personal.

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Some Maintenance Aspects of Viscount Operation

by

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1. Introduction

The importance of maintenance of aircraft in airline operations is emphasised by the fact that, in British European Airways at least, 25 to 30 per cent. of the total direct cost of operating an aircraft is absorbed by maintenance costs. This applies fairly generally to all aircraft in B.E.A.'s fleet, and is also applicable to most of the world's airlines: in the U.S. the proportion is slightly lower, which may be due not to relatively lower maintenance costs, but to relatively higher crew costs there.

These figures serve to show the importance of reducing maintenance costs, and particularly those arising from unscheduled maintenance, to a minimum.

2. Review of Viscount Achievements

The first Viscount, G-ALWE, was delivered to B.E.A. in January 1953, and had, by 30th March 1956, flown 4,750 hours. Delivery of the 26 aircraft of the 701 type was completed by July 1955: delivery of the last three aircraft was considerably delayed by B.E.A.'s agreement to allow the original aircraft to be diverted to Capital Airlines. This decision, while it enabled Capital to begin operations much earlier than would otherwise have been the case, caused serious embarrassment to B.E.A. in the early summer of 1955, due to shortage of aircraft to meet the unprecedented traffic demand.

Before delivery of production Viscounts, many hours of development and proving flying were made on the 630 and 700 prototypes under B.E.A. colours—136 hours on the V.630 G-AHRF and 249 hours on the V.700 G-AMAV. This was, of course, in addition to many hundreds of hours of test and development flying by Vickers-Armstrongs Ltd., and it was largely due to this thorough pre-service programme that only fifteen weeks elapsed between the delivery of the first aircraft and the start of scheduled services. (Other airlines have, of course, since put Viscounts into service even more quickly, but it should be remembered that B.E.A. was the first airline in the world to run scheduled services with gas-turbine powered aircraft, and developed many of the operating techniques from which other airlines have benefited).

By the time scheduled services began in April 1953, five aircraft had been delivered, and once into service, their use increased rapidly. This was partially due to a shortage of other aircraft, but also to the immediate popularity of the aircraft with the travelling public. This was particularly apparent on routes where B.E.A.'s competitors had long claimed the major portion of the traffic—for example London-Copenhagen-Stockholm (S.A.S.), London-Zurich (Swissair) and London-Rome (B.O.A.C.)—so Viscounts were put on to these routes as early as possible. The effect is shown in Fig. 1, which shows the percentage of the total traffic obtained by B.E.A. on these routes before and after the introduction of the Viscount. These increases have been maintained and improved upon since.

It should be remembered that the route to London is, of course, the number one route for every European operator, so B.E.A. has to contend with the cream of the opposition on practically every route, as nearly all of B.E.A.'s trunk routes originate from London.

Figure 2 shows the routes operated by Viscounts in the summer of 1955. It may be considered that some of the internal routes (*e.g.* London-Birmingham) are rather short stage lengths for the Viscount, but the explanation is that it is cheaper to run Viscounts on these routes, using the tax-free kerosine, than to operate Elizabethans, owing to the fuel tax imposed on petrol used on internal services. (Petrol used for international services is exempt from tax).

3. Utilisation

Figure 3 shows the equivalent annual utilisation for each Viscount, plotted monthly, which shows that there has been an increasing rate of utilisation, apart from seasonal fluctuations. It will be seen that the utilisation in the winter of 1955 was very nearly as high as in the summer of 1954.

By some standards these figures may be considered low, and some factors which affect utilisation, particularly on short-haul operations, may be of interest. First and foremost, of course, is traffic demand, which dictates the operational pattern: services must be run

ROUTE	SUMMER 1952 %	SUMMER 1954 %	INCREASE %
LONDON-COPENHAGEN-STOCKHOLM	26·7	46·2	19·5
LONDON – ZURICH	24·1	39·1	15·0
LONDON-ROME	56·3	77·9	21·6

FIGURE 1. Passengers carried by B.E.A. on key routes as percentage of total, before and after introduction of Viscount.

Based on a Lecture given first before the Weybridge Branch in April 1955.

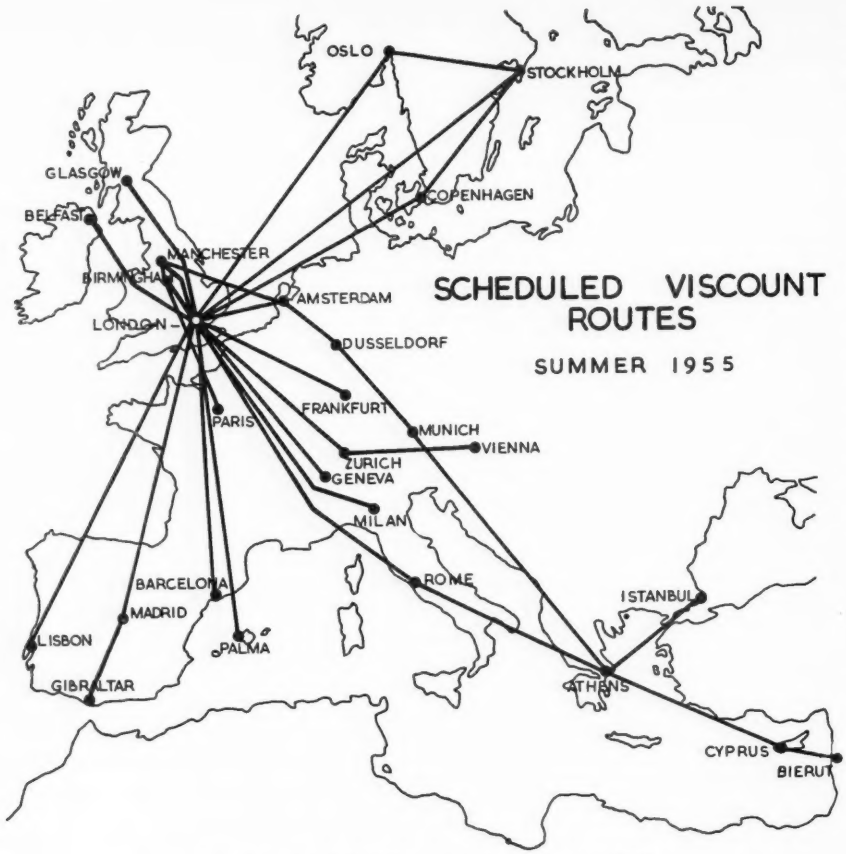

FIGURE 2. Scheduled Viscount routes. Summer 1955.

to suit the customer's convenience and not the operator's.

Traffic demand fluctuates considerably, which makes consistently high utilisation difficult to achieve, and this fluctuation takes three forms in B.E.A.'s operations, due largely to the fact that a high proportion of the services cater for holiday and tourist traffic.

The first of these fluctuations is the hourly one, and

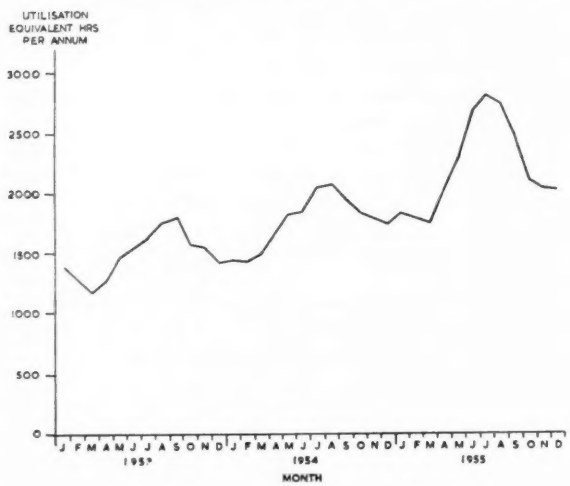
UTILISATION EQUIVALENT HRS PER ANNUM
3000
2500
2000
1500
1000
500
0
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1953
1954
1955
MONTH

FIGURE 3. Viscount utilisation (per aircraft).

Fig. 4 shows the hourly distribution of all departures from London Airport throughout the day on a typical Saturday in August 1954.

It will be seen that there is a peak in the morning, when most of the longer range services depart, to enable passengers to reach their destinations by a reasonable time in the late afternoon or evening. This is reinforced, later in the morning, by shorter range services on which lunch is served in the air, which passengers still regard as a pleasant feature of air travel.

There are other peaks late in the afternoon, for those services on which dinner is served, and another in the evening for those leaving after business hours. Later still, there is another small peak when the night tourist services depart. All of these peaks are dictated by traffic demands.

The effect of these peaks (particularly the morning one) is to call for a very big effort on the part of the maintenance staff at these periods—both on base maintenance to provide aircraft which have been on hangar checks overnight, and on the terminal engineering staff to turn round incoming aircraft or to make serviceable aircraft which have been parked out overnight. (At London Airport, the Engineering Base at which all major maintenance is carried out, is separated both administratively and geographically from the terminal. The latter is treated

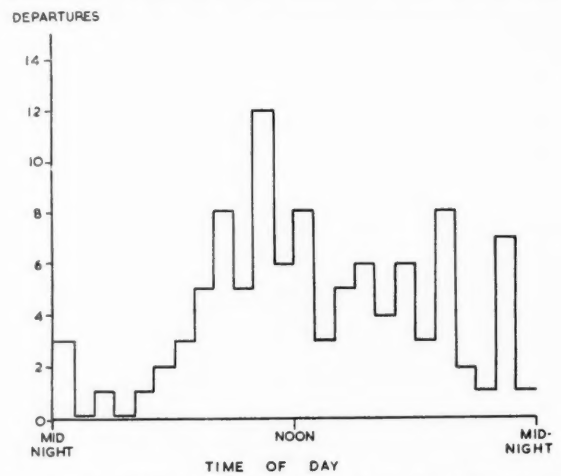

FIGURE 4. Total hourly departures from London Airport during day (peak Saturday—Summer 1954).

similarly in many ways to any other station in the B.E.A. network, although, of course, London Airport station handles far more aircraft than any other station.)

As an example of the concentration of services, three Viscount services were, at one time, scheduled to depart within the space of 15 minutes. (This scheduling was necessary for competitive traffic reasons). This entailed the starting of twelve engines almost simultaneously, necessitating the simultaneous use of three ground power units. Any defect or fault arising at this time was obviously more likely to lead to a delay than if the departures had been more widely spaced.

The second type of fluctuation is the daily one. This is not applicable to every route but is particularly marked on the tourist and holiday routes, especially in summer. There is a sharp increase in traffic demand at week-ends, as is shown in Fig. 5, which shows the daily fluctuation in departures during a week in the summer of 1954.

One advantage of this, which may not be immediately apparent, is that it enables most of the base maintenance staff to work a 5-day week from Monday to Friday, the work being planned to ensure that the maximum number of aircraft are available for service at the week-ends.

Thirdly, the monthly fluctuation, which is shown in Fig. 6, shows a large peak in the summer months, particularly on the holiday routes. Within this total there are individual fluctuations which have to be catered for such as the small peaks at each Bank Holiday period, and on the Swiss services for the winter sports season.

These types of fluctuation are, of course, common to a great many transport undertakings, but not to the same degree in all airlines. B.E.A. is affected by these fluctuations to a far greater degree than B.O.A.C., for example, because of the higher proportion of holiday traffic. The short-haul nature of B.E.A.'s operations aggravates the position.

What is the effect of all these fluctuations on maintenance? Naturally, traffic demand dictates the number of aircraft required, and maintenance must be integrated with this to interfere as little as possible with traffic requirements.

To this end, no minor maintenance (other than that arising from defects, and between-flight servicing) is done during the day, all Checks I being done at night—some away from base. A Check I is the first hangar check, at intervals not exceeding 135 flying hours, which in the summer, at peak utilisation, takes about 3 weeks to a month. During this period the aircraft does not normally enter a hangar, except for a serious defect or engine change. Since the overall rate of defects reported in the Flight Logs on the Viscount is of the order of 40 per 100 flying hours, this means that about 50 such defects must be investigated and rectified between consecutive Checks I, largely, if not entirely, with the aircraft in the open.

Checks II and III are intermediate checks, at 385 and 770 flying hours respectively, for which the aircraft

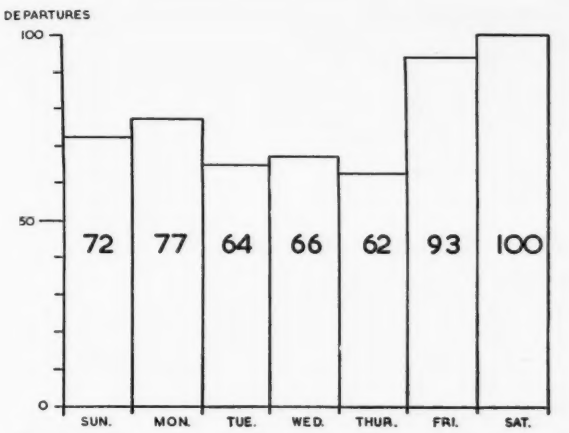

FIGURE 5. Total daily departures from London Airport during week (peak week—Summer 1954).

again come into the hangar, and in this case are worked on by the day shift.

The Check IV, at 1500 hours, is a major check for which the aircraft goes into the specially designed dock, shown in Fig. 7.

The aircraft is usually off service for about 10 days and 1200-1500 man hours are absorbed, depending on the content, which varies from check to check with the amount of Certificate of Airworthiness work involved.

The C. of A. work is done on a progressive basis to avoid the necessity for an annual overhaul, although an annual C. of A. certificate is still issued. The C. of A. cycle is completed in a total of 12,000 flying hours, and is divided into 8 parts, four at 1,500 hours intervals, the other four at 3,000 hour intervals. To spread the work load, the sections of the C. of A. are staggered between aircraft, so that the first aircraft to complete 1,500 hours will have a section A done with the Check IV, the second a Section B, and so on.

It will be readily apparent that since all these checks are in terms of flying hours the amount of work to be

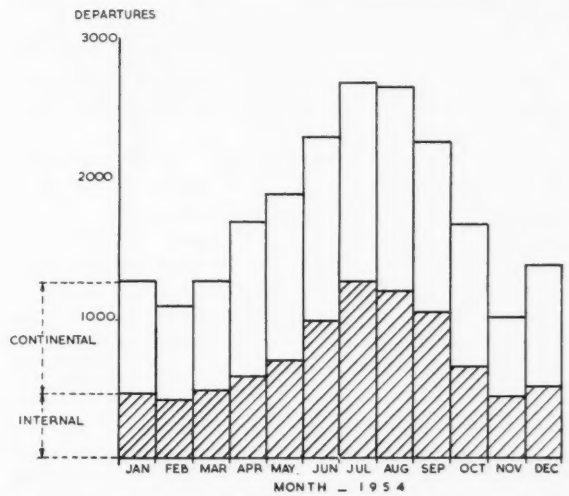

FIGURE 6. Total monthly departures from London Airport during 1954.

FIGURE 7. Check IV. Maintenance dock.

done will be directly proportional to the hours flown, so that in the summer, when utilisation is high, less time will elapse between checks. This is undesirable, as more maintenance work is generated at a time when every aircraft is required for service.

A graph of the planned utilisation for the whole fleet of Viscounts for 1954/5 is shown in Fig. 8, in which the flying hours required show a considerable peak in the summer months. By squeezing the Check IV's closer together both in the early and late months of the year it is possible to provide a much more even flow of maintenance work, as is shown by the lower line. Had this not been done the maintenance commitment would, of course, have followed the utilisation much more closely. It will also be seen that the actual utilisation followed that planned fairly closely.

In addition, major modification and flying training programmes are, as far as possible, carried out in the winter months to even out the work load.

4. Check System Development

The actual content of all checks is under continuous review, with a view to deferring individual items or extending the periods between the checks as a whole whenever possible. On occasion it is, of course, necessary to reduce a check interval or to inspect an item more frequently in the light of experience.

The Viscount reaped the benefit of the work done on the Viking in this direction and therefore started where the Viking left off.

Figure 9 shows how the Check IV interval on the Viking was progressively increased from 400 to 1,200 flying hours. On the Viscount, which started with the Check IV period at 1,200 hours, an increase to 1,500 hours was approved by A.R.B. in 1955 and is now in use. Such check period increases are a most important factor in meeting continually increasing traffic demands without a proportionate increase in aircraft and labour, but depend, of course, on continuing development of the aircraft and maintenance and inspection methods for their implementation without lowering safety standards.

This is an advantage of continuity of development with the same manufacturer, as although the Viking and Viscount are quite different aeroplanes, there are certain fundamentals of design which continue, with development, from one type to another. It is reasonable to assume that all of the development put into one type will be incorporated in its successor, so it is quite justifiable to start where the previous aircraft left off.

from maintenance and inspection standpoints. (This does not, of course, apply to components where there has been a radical change of design, *e.g.* gas turbines instead of piston engines).

5. Engine Overhaul Life Development

As engine overhaul costs can account for up to a third of the total maintenance costs, it is obviously of paramount importance to achieve the highest possible life between overhauls consistent with safety.

With a completely new departure, such as the Dart, it was necessary to begin operations in 1953 with the then comparatively low life of 400 hours; low compared with the Hercules 634 in the Viking which was operating for 1,250 hours between overhauls.

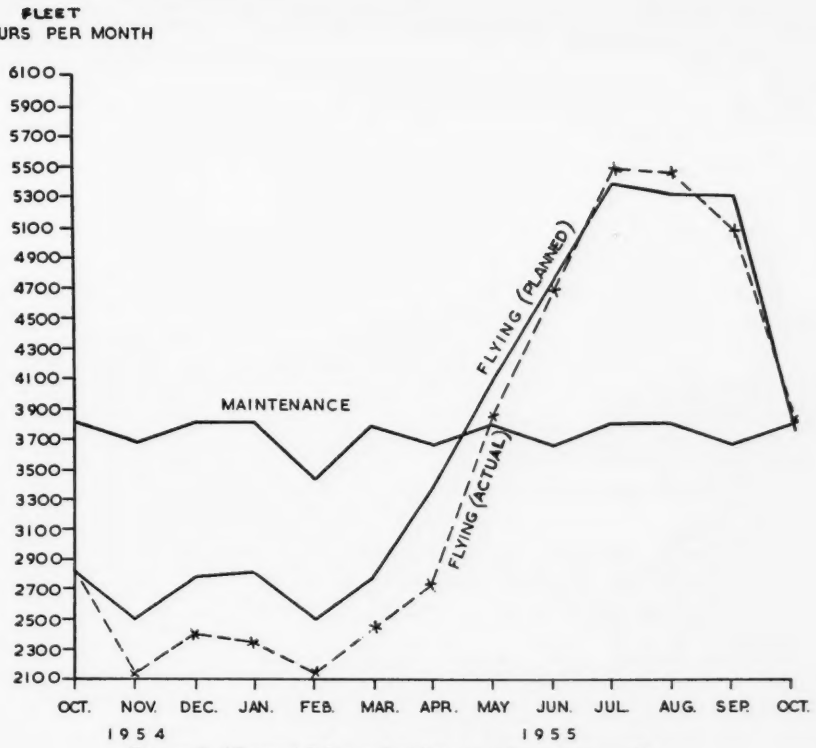

FIGURE 8. Viscount flying and maintenance hours per month.

Even this figure of 400 hours was only approved as a result of extremely exhaustive test flying and test bed development, the former largely in the two Dart Dakota Freighters which amassed over 3,000 engine hours between them.

Figure 10 shows the rapid rate at which the Dart overhaul life has been increased as compared with the Hercules 634. This development has been much more rapid both in elapsed time and in terms of the operational hours necessary to achieve it.

6. Effect of Traffic Demand on Utilisation

On the subject of high utilisation, figures such as 2,500 or 3,000 hours per aircraft are, in fact, actually achieved in a year by some airlines, but usually on airlines having long stage lengths or where there is a steady—and high—traffic demand. Such utilisations are very difficult to maintain throughout the year on short haul operations, with the large hourly, daily and monthly fluctuations in traffic demand already mentioned.

To consider the Viscount operations of Summer 1954: the peak utilisation for each aircraft was at the rate of just over 2,000 hours a year, or at the rate of about 5½ hours a day. To achieve even this, every aircraft had to be serviceable on an average for about 20 hours out of every 24. The fact that only 25 to 30 per cent. of the serviceable hours are actually utilised is, of course, due to the fact that there is little or no traffic demand during many of the hours for which the aircraft are serviceable—particularly at night. That is why, incidentally, such a high degree of convertibility into other roles has been specified on the V.802, with the aim of carrying passengers by day and freight by night *in the same aircraft*, and thus achieving higher utilisation.

A few examples of a typical day's flying for one Viscount may be of interest, to show what is necessary to achieve an average of even 5½ hours per aircraft per day. (This figure takes into account all aircraft on maintenance).

The following are some typical single day's operations for one B.E.A. Viscount:—

London - Milan - London - Zurich - Vienna - Zurich London (14 hours) (often).

London - Zurich - London - Rome - Athens - Istanbul (12½ hours) (often).

London - Milan - London - Frankfurt - London - Birmingham (10 hours) (often).

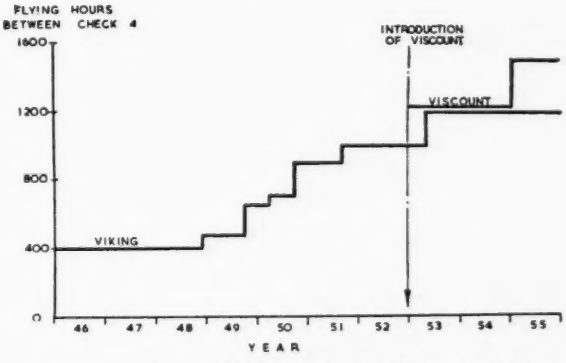

FIGURE 9. Viking and Viscount check periods—check IV.

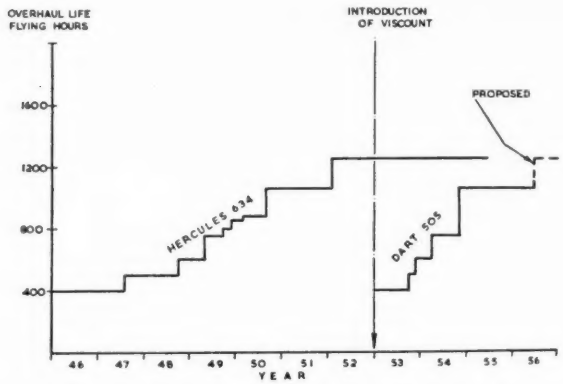

FIGURE 10. Viking and Viscount engine overhaul life.

These are all reasonably long stage lengths (except London-Birmingham), but at the other end of the scale, one aircraft sometimes operates the following routes in one day:—

Belfast - London - Manchester - Birmingham - Paris - Birmingham - Manchester.

These operations, with six transit stops, amass only 6½ hours aircraft utilisation in the day. The best performance in one day by one aircraft was a trip from London to Istanbul and return, which totalled 15¾ hours flying time and occupied, with stops, virtually the whole of the 24 hours.

On the other side of the picture, an aircraft often stands 15 to 20 hours at the terminal at the far end of the route, owing to lack of traffic demand at the time it becomes available for the return trip.

To achieve these daily utilisations calls for turn-round times as low as 45 minutes for a terminal stop, and 30 minutes for a transit stop. This time includes unloading and loading passengers, freight, baggage, catering equipment and meals, as well as maintenance, although this is confined to refuelling and servicing of domestic systems. With such tight scheduling, rectification of any serious defect almost inevitably leads to a delay: delayed departures are, in fact, about 5-10 per cent. of the total departures, depending on the time of year (the winter is usually worse in this respect). On a through trip, it is quite common for a Captain to defer reporting defects until the last leg, if they are of a minor nature, and lists of "Allowable Deficiencies" have been produced which give him a guide as to what he can safely fly without—one for V.F.R. and one for I.F.R. conditions.

On the question of reporting, Captains' reports are not always as explanatory as they might be, although in all fairness it should be pointed out that Captains have many other written reports to produce in respect of each flight.

However, the engineer is sometimes confronted by a somewhat brief report, which has to be the basis of his diagnosis, as the Captain is not usually present to interpret it. One such report simply read: "Vibration —not engines." Occasionally the engineer retaliates: in reply to a Captain's report which stated "Something loose somewhere" the engineer recorded his remedial action alongside as "Something tightened somewhere"!

7. Defect Rates

One obviously major factor in the operation of any civil aeroplane is its susceptibility to defects, and it is generally recognised that an aeroplane, crammed full of ingenious devices as it is, cannot be expected to be free from defects.

This is tacitly recognised by the safeguards and alternative means of operation of services which are insisted upon by the regulatory bodies.

So many factors play a part in any defect which occurs that it is impossible to eliminate defects by design or development action alone, and it should be emphasised here that by no means all of the defects which occur are laid at the door of the aircraft designer. Many so-called defects are not in fact defects at all, but are due to bad diagnosis or bad reporting, which may in turn have been due to lack of time. Some are due to bad maintenance, or absence of maintenance. Other so-called defects may be due to the system of maintenance employed, whereby a number of components may be changed simultaneously to make certain of overcoming the trouble in the minimum time.

But even after allowance has been made for all of these factors, there are still a considerable number which can be attributed directly to design and/or initial manufacture, although it is impossible to establish what was, in fact, the actual cause in every case.

When serious defects occur (or large numbers of minor defects of the same type), detailed investigations are made and in many cases, design action is initiated either within B.E.A. or through the designing firm, to overcome the trouble. It is desirable to employ some yardstick by which the defect susceptibility of an aeroplane can be assessed and although it is very difficult to compare one aircraft in one airline with a different type in another airline, one type of aircraft in different airlines, or different types within one airline can be compared. A firm's Service Department is in an ideal position to make comparisons of the former type, while we in B.E.A. have been rather fortunate (if that is the right word), in putting into service at the same time, two new aircraft of roughly similar size, weight, passenger capacity and so on. One—the Viscount—is powered by 4 gas-turbine engines: the other—the Elizabethan—by 2 large piston engines. We have therefore been in a position to compare the defect performance of these two aircraft and have been able to compare, where applicable, the defect performances of identical equipment fitted to both aircraft, with some interesting results.

The yardsticks used are as follows:—

(*i*) Flight Log entries per 100 flying hours.

(*ii*) Components changed on Routine checks per 100 flying hours.

The former is an indication of the number of incidents reported, mostly by flying crews, *between*

hangar checks. These snags may or may not be confirmed: they may be rectified by adjustment or change of component, or no fault may be found. But they are an indication of something having been amiss which the Captain has thought worthy of attention, and can, I think, form a genuine basis for comparison between one aircraft and another *within the same airline.*

Major defects on routine checks are largely rectified by change of component, which is the second yardstick. This is only a rough guide, as a "component" may vary from an air charging valve to an engine, so that one section cannot be fairly compared with another on the same aircraft. But since the components used on one system on one aircraft are roughly the same type of components as those used on the same system on another aircraft, again a rough comparison can be made.

Figures 11 and 12 show comparisons plotted monthly, of defect rates on these two bases. Fig. 11 shows the total number of Flight Log entries per 100 hours for each aircraft, and it will be seen that these now follow each other fairly closely, the present Viscount rate being about 35-40 entries per 100 flying hours, or one every 2½-3 flying hours. Since the average Viscount flight time is about 2 hours, this amounts to one entry on almost every flight. It will be seen that there has been a marked improvement in this rate on both aircraft, and it should, of course, be borne in mind that the Elizabethan has had at least a year more of development in service than has the Viscount. The graph shows that although the Viscount rate is slightly worse than the Elizabethan at the present time, it is very much lower than the Elizabethan was at a comparable stage in its life.

Figure 12 shows a similar graph for the number of components changed on Routine Checks, reduced to a common basis (per 100 flying hours). These component changes are in addition to those which may result from Flight Log defects. Figs. 13 and 14 show these figures broken down into separate systems for each aircraft: there is little difference in the incidence of defects in each group between the aircraft: electrics account for a slightly higher proportion of defects on the Viscount as it is a more "electric" aeroplane: the employment of gas turbines in the Viscount appears to have had little effect on the rates for either instruments or the airframe.

By far the greatest fundamental difference between the two aircraft is, of course, the employment of gas turbines in the Viscount. Although this has given rise to new defects, it has also largely eliminated the most serious and persistent defects associated with piston engines—those on the ignition system. It is noteworthy that even the simple ignition system on the Dart, which is used merely for starting, was, in the early days, responsible for quite a high proportion of defects and delays. A completely new and improved ignition system is now fitted, but even the original system accounted for nothing like the delays that were experienced due to ignition trouble on the Viking.

In 1952 (by which time a considerable amount of development had been put into the Hercules ignition

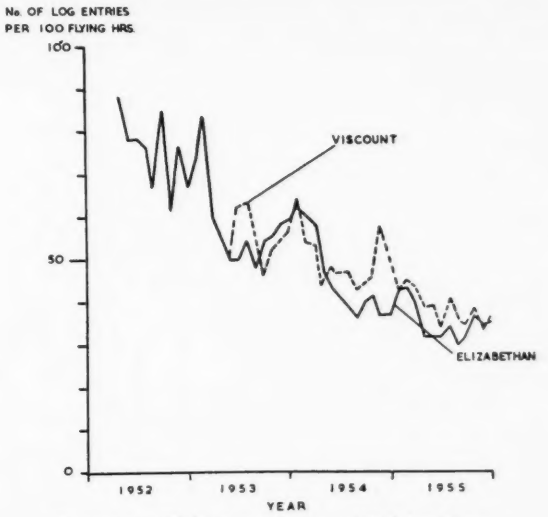

FIGURE 11. Flight Log entries per 100 flying hours.

system on the Viking) there were 870 delays due to ignition in 84,000 flying hours, or approximately one out of every 75 departures.

On the Viscount in 1954, there were 93 ignition delays in 31,400 hours, or approximately one out of every 150 departures.

The Viscount, therefore, showed half the delay rate with twice the number of engines—a very welcome improvement, since the full effect of development had not yet been felt.

On the other side of the medal, the present very long ground runs required to carry out inter-connection checks (*i.e.* correct relationship between r.p.m., fuel trimming and J.P.T.), are one of the most serious maintenance aspects of the gas turbines in the Viscount, and

FIGURE 12. Components changed on routine check per 100 flying hours.

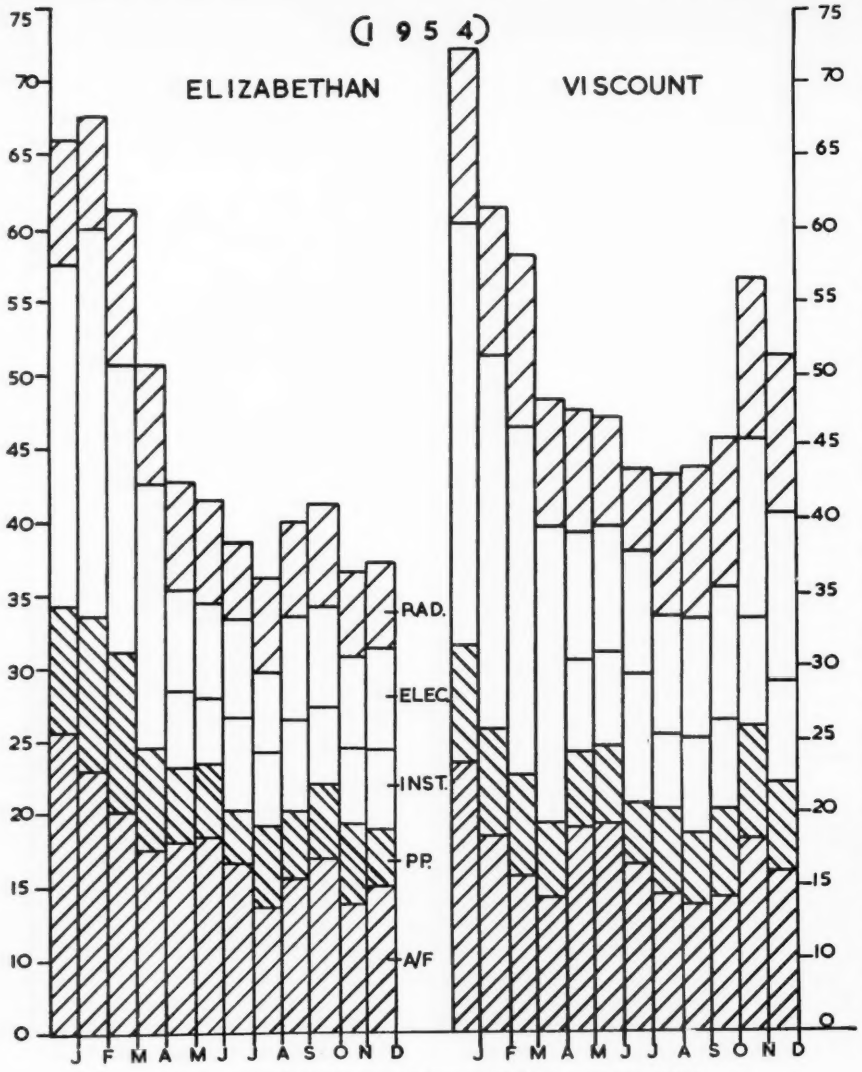

FIGURE 13. Elizabethan and Viscount Flight Log entries (1954).

local residents near London Airport would probably agree. These can take anything from 40 minutes per engine upwards—they have taken all day on occasion —and require a really skilled engineer to carry them out.

Because of complaints of noise, a log is kept of all engine ground runs at London Airport stating why these were necessary in order to answer Ministry of Transport and Civil Aviation queries brought about by irate residents ringing up at any hour of the day and night. The opening of the Central Area at London Airport has probably mitigated this nuisance to some extent.

8. Man Hours Per Flying Hour

Routine maintenance and inspection, together with the rectification of defects, add up to a requirement for man-hours of labour of various categories. Due to B.E.A.'s planned and rate-fixed maintenance system, it is relatively easy to record and analyse the overall work content of maintaining the aircraft, and these figures can be broken down to trades, checks and so on to enable a continuous appraisal to be made.

Figure 15 shows the total direct maintenance man hours per flying hour absorbed by the Viscount since its introduction. It will be seen that the overall figure, after an initial steep improvement, has increased gradually since. This is due to the fact that the Viscount has not yet been in service long enough for a full maintenance cycle to have been completed for all aircraft: until this is achieved the figures can be somewhat misleading. The hangar work has therefore been plotted separately, which does show a continuous improvement: the gap between the hangar work and the total work, which represents overhaul work, has been increasing as the aircraft get older, and will continue to increase until the flow of defective and time-expired components is stabilised. After this, the normal improvements due to development of the aircraft and improved maintenance techniques should begin to make themselves felt.

Figure 16 shows the total direct labour cost, in terms of man hours per flying hour, broken down into aircraft systems, for the last 6 months of 1954. The large slab labelled "Miscellaneous" is largely accounted for by aircraft cleaning, which absorbs a very large amount of time, and is not effective for very long once the aircraft is left out in the open.

9. Maintenance Costs Per Flying Hour

As mentioned earlier, maintenance costs represent about 30 per cent. of the direct cost of operating a Viscount in B.E.A.

At present the total maintenance cost is about £30 per flying hour, out of a total direct operating cost of £100 per hour.

Figure 17 shows how this maintenance cost is made up, and it will be seen from this that a large proportion is accounted for by the outside overhaul of engines, and hence how important it is (*a*) to utilise the existing life of engines to the full and (*b*) to extend this life as rapidly as possible, consistent with safety. One not inconsiderable advantage of a four-engined aircraft is

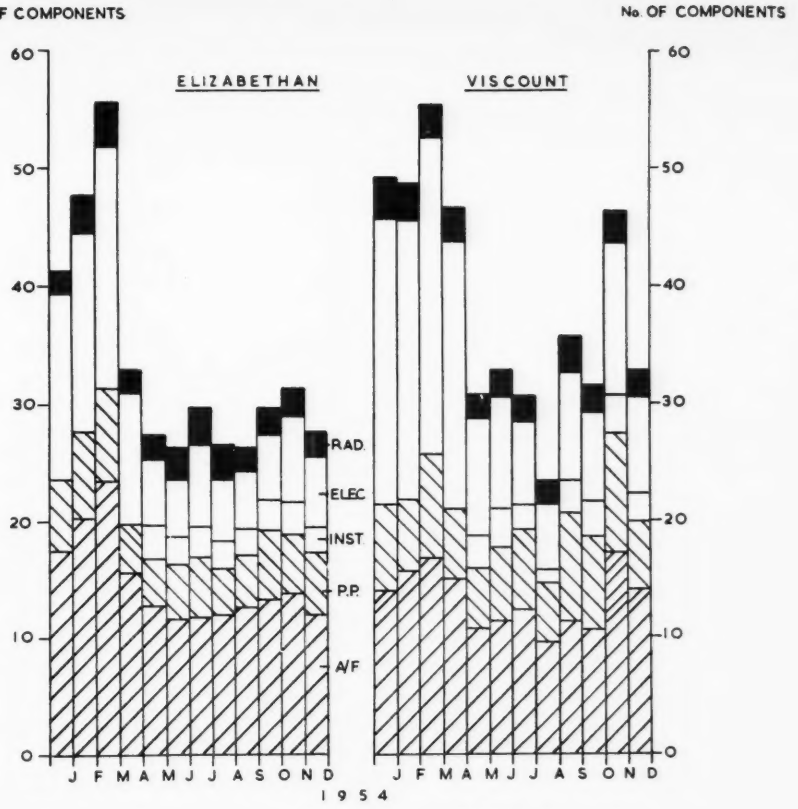

FIGURE 14. Components changed on routines per 100 flying hours—by systems.

that it probably allows of more rapid development of engine overhaul life than a twin-engined aircraft, since if there should be an engine failure due to increasing the overhaul life too fast, at least it will only represent a loss of 25 per cent of the power, instead of 50 per cent. Another incidental advantage is that of being able to ferry a four-engined aircraft back to base on 3 engines, which cannot be done when an engine failure occurs on a twin, and either keeping spare engines dotted about Europe or flying them out can be an expensive business.

Although there has been a considerable reduction in cost of maintenance per flying hour since the introduction of the Viscount, this has been offset to a certain extent by the increased overhaul costs as aircraft become older, as already shown in terms of man hours. One would imagine that maintenance costs would naturally reduce with time (if labour and material costs remained static) simply through increased familiarity with the aircraft. This is not entirely the case, however: past experience shows that there is an initial stage of disruption during the change-over period from one type of aircraft to another, but this is more than offset by the newness of the aircraft and the fact that (if the spares have all been ordered and delivered to schedule) there may be spares available for twenty aircraft while only operating two or three.

We then seem to get a period of rapidly improving conditions where we are getting to know the aircraft, the manufacturers have learnt how to build it, and modifications have been raised to overcome the teething troubles that always appear in actual service. Then, when everything appears to be going nicely, we start to get the really serious defects that come with age—often, of course, due to fatigue, and of the type which can, and sometimes do, ground the aircraft.

However, apart from mere familiarity with the

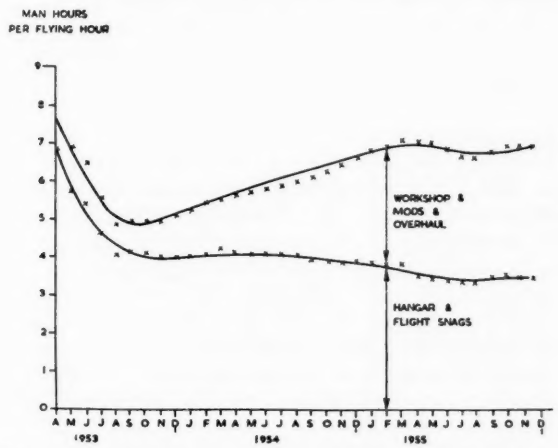
MAN HOURS PER FLYING HOUR
WORKSHOP & MODS & OVERHAUL
HANGAR & FLIGHT SNAGS
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1953
1954
1955

FIGURE 15. Viscount total direct maintenance—man hours per flying hour.

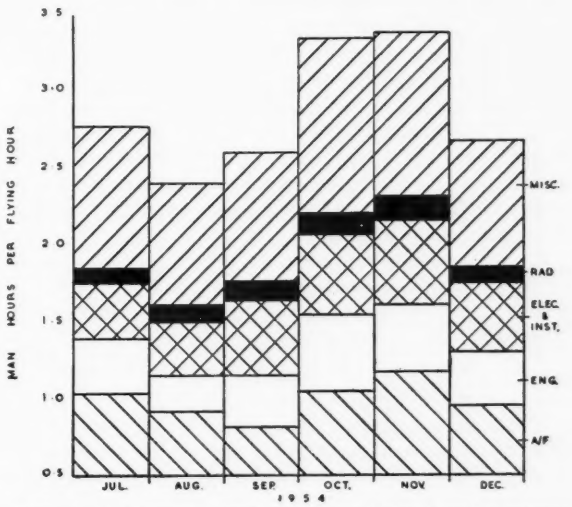

FIGURE 16. Viscount—direct man hours/flying hour by systems —last 6 months 1954 (Check I-IV only).

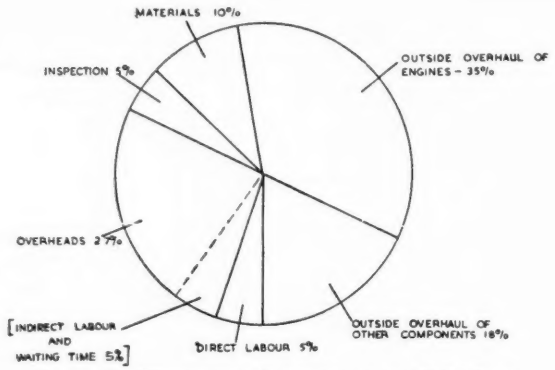

FIGURE 17. Viscount—maintenance cost per flying hour (approximate average for 1954).

aircraft, continual development, leading to increases in check periods, overhaul times, and so on, reduces the maintenance costs per unit. Modifications are continually being raised within B.E.A. (quite separately and distinctly from manufacturers' modifications) to improve the aircraft from maintenance and operating aspects. Over 400 internal modifications have been raised on the Viscount within B.E.A. of which 300, or 75 per cent., were to improve maintenance facilities or to overcome defects. (Many of these were, of course, of quite a minor nature).

10. Defect Rates and Utilisation

Utilisation appears to have a marked effect on defect-rates, and hence on maintenance costs. This probably explains why longer haul operators often have lower defect rates per flying hour, since many defects can only be recorded once per flight, regardless of its duration. For B.E.A. the average Viscount flight time is about 2 hours or slightly less: in B.O.A.C., for example, it is from $4\frac{1}{2}$ to $6\frac{1}{2}$ hours depending on the aircraft and route.

Figure 18 shows the Viscount Flight Log defect rate plotted against the monthly rate of utilisation, for 1954. The defect rate appears to be roughly inversely proportional to the rate of utilisation, so that when these two factors are multiplied together a horizontal line results. This lower line shows, in effect, the number of defects which would occur per aircraft per annum if the defect rate for any particular month were to be constant throughout the year, coupled with the equivalent annual utilisation applicable to that month. This effect is not quite so marked in 1955, but nevertheless, increased utilisation has not led to a proportionate increase in the number of defects: in fact, the total *number* of defects has been held more or less constant with greatly increased utilisation.

11. Component Overhaul Lives

We have, in B.E.A., been largely responsible for bringing about quite a different outlook in this country on this subject, and have, at the present time an average overhaul life of about 4,800 hours on the 120 time-lifed Viscount components.

This compares with an average of about 1,500 hours for Viking time-lifed components in 1950, and even this was after several years of development.

In effect, we are now very close to "On Condition" maintenance of many time-lifed components: *i.e.*, although "lifed" the lives are so high that the components are quite likely to be removed on account of their condition before becoming time-expired.

12. Design for Maintenance

This title is unfortunately in common use, but "Design for absence of maintenance" should be the goal. Obviously, the ideal to aim at is an aeroplane which requires no maintenance at all. But as some maintenance is bound to be necessary, design for ease of, or minimum, maintenance, appears to depend on three main factors: (*i*) Reliability, (*ii*) Ease of rectification (if and when defects occur), and (*iii*) Ease of servicing.

12.1. RELIABILITY

Long life between overhauls, with freedom from defects in between, is the operator's requirement, and he wants components that will function for these long periods without frequent inspection, checking or lubrication, particularly where a component, for other reasons, must be located where it is inaccessible. The components on the Viscount are, by and large, the products of the same component manufacturers who supply components for other British aircraft, and as far as we can see, their performance is about the same on the Viscount as on the Elizabethan. The different vibration characteristics appear to have no significant effect, the conclusion from which is the fairly obvious one that vibration is far from being the only, or even the most serious factor, causing defects.

Figure 19 shows a comparison between identical components fitted to both the Viscount and Elizabethan. Where the defect rate on the Viscount component is worse than the Elizabethan it is plotted above the base line in terms of percentage, the base line representing 100 per cent, or equality. Those below the base line indicate a worse state of affairs on the Elizabethan. Most of the components do not differ widely in defect performance: those on the extreme right hand side, which appear to perform very badly on the Elizabethan, are actually used in quite different applications although they are identical components.

The clock appears to perform much better in the Elizabethan than in the Viscount: it may, of course, be vibration that keeps it going!

On the structural side a number of fairly serious defects have been experienced which were caused, or aggravated by, poor detail design. Some of these quite serious defects stemmed from such small points as rapid change of section on a plug end; failure to call for chamfering on both internal and external faces of holes through a double lug; and the clamping of flat castings down on to curved surfaces without adequate precautions against distortion of the casting.

These are all types of design fault which have been with us since aircraft began, but have become increasingly serious with the use of continually higher strength aluminium alloys, with their susceptibility to fatigue. Almost invariably every major failure experienced nowadays is a fatigue failure, rather than an ultimate failure, which says much for the high standard of design requirements and the accuracy with which they are met, both by calculation and by testing. It is now taken for granted that structural strength will be more than adequate to meet all the direct loads experienced in service, and things seldom break nowadays for the classic cause so often quoted in 1022's; the defect was often described as:—" Component broke ": and the " Probable cause of failure as ' Not strong enough! ' "

However, it seems that in the future it will be impossible to stress fully any component entirely within the four walls of the Stress Office, and that although the direct stressing can be done beforehand, in many cases it will be necessary to know the vibration characteristics of the aircraft, and the routes, frequencies, stage lengths, and so on, over which it will be flown, before really representative tests can be carried out.

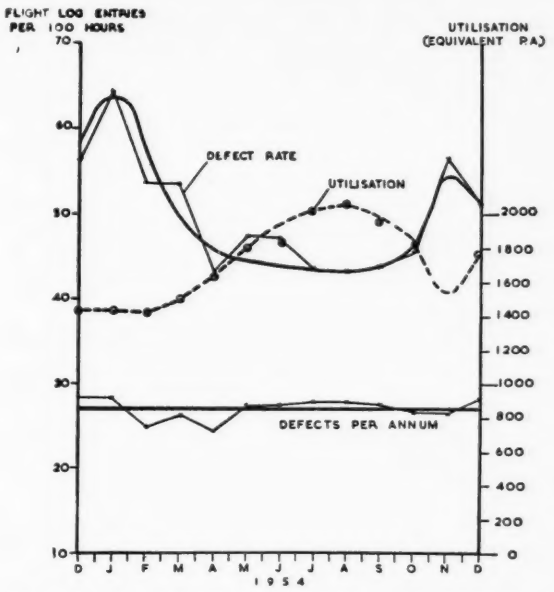

FIGURE 18. Viscount defect rate (Flight Log) and utilisation.

12.2 RECTIFICATION OF DEFECTS

The method of rectifying defects adopted by most airlines is by direct change of component, so far as possible. This is based partly on experience, partly on expediency. Past experience has shown components to be unreliable and since the method of changing components more often than not rectifies the defect, the system persists. This method needs very strict control, and must not be carried to extremes. To rectify a fault on a motor-car, one could (and might) do it by a process of elimination by changing say the plugs, distributor, coil, fuel pump, carburettor and so on until the defect was rectified. One might well use this method, not one component at a time, but all together, if there were sufficient emphasis on the urgency of the situation, if unlimited spares were available, and if cost was no object. If on the other hand the car was not required for a week and there were no spares available in any case, one would probably spend a considerable time merely diagnosing, checking, cleaning, adjusting and so on, and might well cure the defect without changing a single component.

Airline maintenance lies between these two extremes, but with a bias towards excessive change of components because of the usual urgency of the situation. This varies, of course, but when a defect occurs just before departure it may be worth going to almost any lengths to rectify the trouble by multiple component changes, particularly if no stand-by aircraft is available. Schedules are so closely integrated, particularly in the summer, that the late departure of one aircraft may have a " snowball " effect and disorganise many other services as well.

As previously stated, the system needs close control; indiscriminate changes of component on a major check in the hangar, with a reasonable amount of time, facilities, tools, test rigs and so on available, would obviously not be justified. Another corollary to the system of rectification by change of component is that workshop facilities must be available to test and overhaul removed components quickly, to verify first of all that removed components are in fact defective, and if so to rectify them and send them out again *with a full life* as soon as possible.

In the early days of Elizabethan operation in B.E.A., when maintenance facilities were in the process of being removed to London Airport, the situation was aggravated by the high incidence of defects on a relatively undeveloped aircraft, coupled with lack of experience on the part of the maintenance personnel. This led to an excessive number of component changes and in the absence of convenient workshops, most of these components were returned to manufacturers for overhaul. This process, which was in many cases extremely lengthy—components could be out of commission for three months in some instances—led to all spares being absorbed if repetitive defects occurred: in fact, a large proportion of B.E.A. spares at that time was distributed over British Railways network.

With our own workshops now at London Airport the position is much improved, but since the workshops cannot test *every* component before beginning work on it, to verify whether in fact it was faulty, it is inevitable that a certain amount of so-called " unnecessary " work is done in rectifying components that were, in fact, perfectly serviceable.

From a design standpoint, the significance of this method of maintenance is to call for easy replacement of components when defects occur. In detail, this requirement has several aspects—a component must be accessible before it can be changed. Operators would naturally prefer more and larger access panels

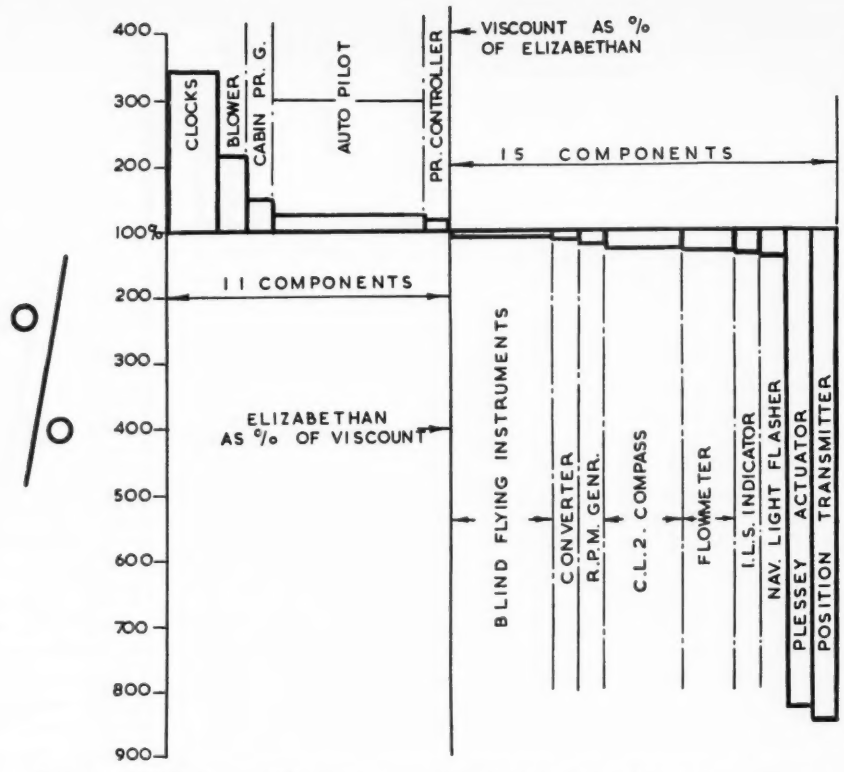

FIGURE 19. Elizabethan and Viscount—comparison of defect rates on identical components.

for ease of maintenance, but design trends are in the opposite direction. Numerous holes and cut-outs cannot be tolerated in the thicker skins now commonly employed: essential cut-outs must either be heavily reinforced, or the panel made stress carrying, which militates against rapid removal. The grouping of components, with large access panels to each group, is probably the solution, but the groups must be completely separated (*a*) because different tradesmen work on them and (*b*) electrics, for example, should be separated from hydraulics, and oil from oxygen. Access panels should, wherever possible, be large enough both to see and to work through simultaneously. (Being able to see, but not feel, or vice-versa is very frustrating). Where not stressed, access panels should be quickly releasable—preferably by *one* fastening—and should be attached by cable (*not* by so-called chandelier chain) to the structure. If hinged, they should not be restricted by the hinge from fully opening, otherwise the hinge will inevitably get damaged.

Very little imagination is usually shown in the design of component attachments, quick release attachments being the exception rather than the rule. Not enough use is made of anchor nuts in this connection which, apart from any other advantages, often reduce the number of men required to change a component from two to one, which is fairly essential on an outstation if there is only one man there. For the attachment of actuators clevis pins are now universal in B.E.A. in place of bolts: in fact, all short-lifed or continuously running components such as actuators, inverters, and so on, merit special consideration for rapid removal.

Adequate lubrication to reduce wear on moving parts to a minimum should be provided, coupled with provision for rectification (by allowing for the fitment of bushes) when wear does occur. Another associated point is design for vulnerability as a unit—*i.e.* when removed from the aircraft. The pressure controller, for example, has no base on which to stand when removed from the aircraft and must therefore rest on some vulnerable and highly sensitive part. Probably as much damage has occurred to pressure controllers in handling as has occurred *in situ*. A considerable number of cabin windows (costing about £50 each) were also damaged due to the vulnerability of the dry air system connection when the window was removed from the aircraft. Although very small design points, such shortcomings can lead to maintenance costs out of all proportion to the cost of the design change.

12.3. ROUTINE SERVICING

Routine servicing, by which is meant the re-charging and replenishment of all systems, and ground handling has to be carried out so often on a civil aircraft, particularly if used on high frequency short haul services such as B.E.A.'s, that it should be simplicity itself. This is far from always being the case. It is hoped to achieve a utilisation of at least 2,000 hours a year from our Viscounts, with a life of at least 10 years—a total life of 20,000 hours. The average duration of a B.E.A. Viscount flight is about 2 hours, and most of these servicing operations have to be done between each flight, so that access panels to servicing points have to be opened and shut, connections screwed on and unscrewed 10,000 times in the life of the aircraft. One could quite reasonably expect such fittings to last the life of the aircraft, but it is obvious that some of them would be unlikely to survive even 1,000 operations, which represents only one year's operations. It must be remembered that servicing operations are largely carried out by unskilled labour, without tools, and in all conditions of weather. (It may be of interest to point out that unskilled labour can only be used if no tools are required. If even a set spanner is required, unions insist that a skilled operator must be employed.)

The use of tools, and particularly of special tools, for all routine servicing operations, should therefore be avoided. As an example, the original fuel tank water drains, which have to be checked after every flight, require a special tool to open them. Operators cannot

usually spare the time to requisition special tools from stores which may be a considerable distance away from the scene of operations, so a screwdriver is used which usually slips off, as the numerous scratches around these points on the undersurface of the wing on any B.E.A. Viscount will testify. Exhortations to desist from such practices have little effect and in any case, prevention is better than cure.

On another aeroplane (not the Viscount) of which the prototype visited London Airport for appraisal, normal turn-round servicing was carried out once only. Filler caps were attached by the ubiquitous brass chandelier chain, which snapped on the very first occasion used, by wrapping itself up. This would inevitably be followed by loss of the cap, through someone forgetting to replace it.

There are one or two points worth mentioning in connection with routine servicing on the Viscount.

The windscreen de-icer system, which has to be topped up fairly frequently in the winter, was originally fitted with a small diameter screw connection designed for air charging, and therefore self-sealing. Owing to the small bore, and back pressure brought about by the self-sealing facility, it was found that the small hand-pump operated bowsers used, were not powerful enough to fill the system—or at the best, only very slowly. A further point was that the filter was directly below the tank so that every time the filter required cleaning or removal, the tank had to be drained.

Designers seem to have a predilection for excessive lengths of fine thread on filler caps: the Viscount hydraulic tank filler cap has 5 complete turns of fine thread, necessitating 10 complete turns to undo it and do it up again. (Pressure refilling facilities are also provided, but pressure bowsers are not available all over the Continent, so that manual filling is frequently used).

Water systems are a continuous source of trouble. Fine thread screw-caps on the outside skin inevitably freeze, and are often provided with a smooth exterior surface and placed in a small box so that a gloved hand cannot get a grip on them. Venting, too, is often inadequate—and leads to tanks collapsing under large differential pressures. There seems to be no apparent reason for inadequate venting.

So far as possible, no routine servicing, or minor maintenance, should necessitate access to the passenger cabin. If frequent access to the interior is necessary, chairs and upholstery will quickly become contaminated with dirt and grease, even if maintenance personnel are only walking through the cabin.

Summing up, the broad requirements for ease of maintenance are:—

(1) Make it simple rather than clever.
(2) Use reliable components.
(3) Can you see it? and get at it?—both together?
(4) Can one man replace it?
(5) Will it stand 10 years handling?
(6) Can it be done in the cold and wet? without special tools?
(7) Keep it out of the cabin.

13. The Future

The unforgivable sin in aircraft design is to repeat past mistakes. There appears to be an unlimited supply of new bricks waiting to be dropped, and no doubt many will be. But at least we should try not to drop the same ones again.

The importance of the true facts getting back to the designer cannot be over-emphasised, and this emphasises the need for a really live Service Department, working in close collaboration with, and respected by, the Design Department.

If any reasonably serious defect occurs which the Senior Designer concerned is not made aware of, it indicates that the channels of information are not as good as they might be.

14. Conclusion

Although the operator plays only a secondary role in the design and development of civil aircraft there is no substitute for experience gained in line service; no amount of flight testing, proving flying, maintenance trials and so on will provide the same answer, valuable though such tests may be.

B.E.A. and B.O.A.C. are usually the first operators of any new British aircraft which they adopt: both have operated American aircraft and are in any case in competition with other operators who have used American aircraft almost exclusively up to now. There is no doubt that American civil aircraft have, in the past, led the world, due largely to the much more highly developed and competitive airline system in the U.S. This applies particularly to the design of civil aircraft as passenger-carrying transport vehicles, rather than in the structural and aerodynamic spheres.

B.E.A. and B.O.A.C. are therefore in a strong position not only to state their own requirements, but to advise British manufacturers of the features that foreign operators are likely to require. It behoves British manufacturers to take note of any such comments which will, if ignored, probably be raised with much greater emphasis by foreign operators later.

For the same reason, defects which occur in the early stages of operation by the Corporations should not be dismissed as "isolated cases"—one defect in the first 1,000 hours may presage forty such defects per annum in a fleet of twenty aircraft each flying 2,000 hours a year.

The difficulties of reconciling all these different, and often conflicting, requirements, and of producing something that works are, of course, fully recognised. The criticisms made are insignificant compared with the positive achievement of designing and producing the Viscount and getting it into service on the airlines of the world in such a relatively short space of time.

ACKNOWLEDGMENTS

The author would like to thank British European Airways for permission to present this paper: the views expressed are entirely his own. Acknowledgments are also due to R. W. Pollard and H. W. Owen of B.E.A. for assistance in compiling statistics and graphs.

TECHNICAL NOTES

Contributions to this Section of the JOURNAL *will be eligible for Journal Premium Awards and will normally be published within two months of being received.*

Stresses in Shock Absorbers

by

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(Rotol/British Messier Ltd.)

THIS INVESTIGATION is concerned with the stresses in a hollow circular cylinder of constant wall thickness, and closed by flexible plates, also of constant thickness. The cylinder is subjected to the combined action of an internal pressure and an axial force, both of which are statically applied. Although the particular case envisaged is that of a shock absorber, there are other engineering elements to which the analysis is applicable. Any closed circular cylinder of constant wall thickness subjected to an internal pressure is within the category. In a paper[1], Dr. D. M. A. Leggett investigated the case of an oleo-pneumatic shock absorber with rigid end plates, and what follows is an extension of his paper. As would be expected, the flexibility of the end plates causes a reduction in the flexural stress. The notation of the paper referred to is substantially used here.

NOTATION

- t thickness of cylinder wall,
- r mean radius,
- z radial displacement of a point in the middle surface of wall,
- p axial pressure,
- q internal pressure,
- E Young's modulus of the material of cylinder and plate,
- μ Poisson's ratio,
- D flexural rigidity of cylinder wall,
- F flexural rigidity of plate,
- x and z are the co-ordinate axes.

Other quantities are defined in the text where they first appear.

INTRODUCTION

Figure 1 shows the essential features of the mechanism analysed. The two cylinders A and B, one containing oil and the other air and oil, are free to slide on one another. C is a floating plunger, and the end H of cylinder B has an orifice through which oil can be forced. The oil and the air are initially compressed, it therefore follows that when a load is applied to the mechanism so that it causes the ends J and K to be forced towards one another, the pressures in the fluids will be increased.

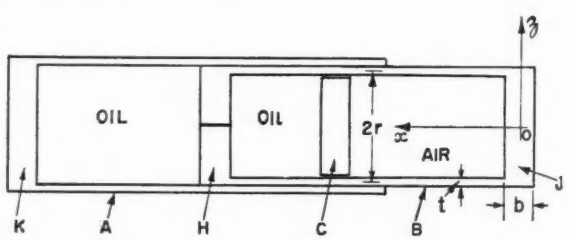

FIGURE 1.

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STATEMENT OF THE PROBLEM

The problem considered is the behaviour of the cylinder B when subjected to an axial pressure p on the wall, and an internal air pressure q.

The circular plate J is considered to be an integral part of the cylinder, which here means that the plate is neither shrunk on nor screwed on.

The functioning of the shock absorber induces the following four distinct types of stresses in the cylinder wall:

- (a) hoop stress resulting from the internal pressure q;
- *(b) stresses resulting from the pressure p which tend to cause buckling;
- (c) flexural stresses induced by the pressures p and q and the effects of the restraint on the circumferential expansion on the cylinder by the circular plate J;
- (d) flexural stresses in the plate J.

THEORETICAL SOLUTION

The radial displacement of the middle surface of a hollow circular cylinder, resulting from a simultaneous action of an axial pressure p and an internal pressure q, must satisfy the differential equation

$$D\frac{d^4z}{dx^4}+pt\frac{d^2z}{dx^2}+\frac{Et}{r^2}z=q+\frac{\mu}{r}pt \quad . \quad (1)$$

and, as the end circular plate is flexible, the differential equation

$$\frac{d}{dz}\left[z\frac{d}{dz}\left\{\frac{1}{z}\cdot\frac{d}{dz}\left(z\frac{dx}{dz}\right)\right\}\right]=\frac{q}{F}z \quad . \quad (2)$$

must also be satisfied.

The complete solution of equation (1) is

$$z=(A\cos\phi x+B\sin\phi x)e^{\theta x}+(L\cos\phi x+N\sin\phi x)e^{-\theta x}+ \\ +\frac{r^2}{Et}\left(q+\frac{\mu}{r}pt\right) \quad . \quad . \quad (3)$$

the last term being a particular integral, and the remaining

*This condition has not been investigated because Dr. Leggett in his paper states that " Buckling could not possibly occur. . ."

terms the complementary function in which A, B, L, N are arbitrary constants.

A and B must be zero otherwise the displacement z would increase without limit. Equation (3) therefore reduces to

$$z=(L\cos\phi+N\sin\phi)e^{-\theta x}+\frac{r^2}{Et}\left(q+\frac{\mu}{r}pt\right) \quad . \quad (4)$$

where (*i*) $$\theta=\left\{-\frac{1}{4}\frac{pt}{D}+\frac{1}{2}\left(\frac{Et}{r^2D}\right)^{\frac{1}{2}}\right\}^{\frac{1}{2}}$$

(*ii*) $$\varphi=\left\{\frac{1}{4}\frac{pt}{D}+\frac{1}{2}\left(\frac{Et}{r^2D}\right)^{\frac{1}{2}}\right\}^{\frac{1}{2}}$$

For convenience write

(*iii*) $$K=\frac{r^2}{Et}\left(q+\frac{\mu}{r}pt\right)$$

then (4) becomes

$$z=(L\cos\phi x+N\sin\phi x)e^{-\theta x}+K, \quad . \quad (4a)$$

At $x=0,\ z=0$

therefore $$z=(N\sin\phi x-K\cos\phi x)e^{-\theta x}+K, \quad . \quad (5)$$

therefore

$$\frac{dz}{dx}=\{(\phi K-\theta N)\sin\phi x+(\phi N+\theta K)\cos\phi x\}e^{-\theta x} \quad . \quad (6)$$

$$D\frac{d^2z}{dx^2}=D[\{(\theta^2-\phi^2)N-2\theta\phi K\}\sin\phi x-$$
$$-\{(\theta^2-\phi^2)K+2\theta\phi N\}\cos\phi x]e^{-\theta x} . \quad (7)$$

Equations (6) and (7) give respectively the tangent and the moment at any point along the cylinder wall.

At $x=0$, (6) and (7) become

$$\frac{dz}{dx}=\phi N+\theta K \quad . \quad . \quad . \quad . \quad . \equiv Z \text{ say} \quad . \quad (8)$$

$$D\frac{d^2z}{dx^2}=D\{(\phi^2-\theta^2)K-2\theta\phi N\} \quad \equiv Y. \text{ say}$$
$$. \quad . \quad . \quad (9)$$

We want the expressions for the tangent and the moment from (2).

The integration of (2) gives

$$x=\frac{q}{64F}z^4+\frac{A_1}{4}z^2(\log z-1)+\frac{A_2}{4}z^2+A_3\log z+A_4$$
$$. \quad . \quad . \quad (10)$$

$$\frac{dx}{dz}=\frac{q}{16F}z^3+\frac{A_1}{4}z(2\log z-1)+\frac{A_2}{2}z+\frac{A_3}{z} \quad (11)$$

$$F\frac{d^2x}{dz^2}=\frac{3}{16}qz^2+\frac{A_1F}{4}(2\log z+1)+\frac{F}{2}A_2-\frac{F}{z^2}A_3 \quad (12)$$

A_1 must be zero otherwise the shear would be infinite at $z=0$ and A_3 must also be zero for a finite displacement at $z=0$.

There are three remaining arbitrary constants to be determined: N from the equations of the cylinder, and A_2 and A_4 from the equations of the plate.

The displacement at the boundary of the plate must be zero, also the tangent to the plate, and the moment in the plate at its boundary must have the same absolute values as the corresponding quantities for the cylinder at its junction with the plate. That is, the boundary conditions are:

(*iv*) $x=0$ (*v*) $dx/dz=-Z$

(*vi*) $Fd^2x/dz^2=-Y$ at $z=r$.

Inserting these boundary conditions in (10), (11) and (12) respectively, we find that

(*vii*) $$A_2=-\frac{1}{\Delta}\left\{\frac{qr^2}{8F}\left(3+2r\theta\frac{t^3}{b^3}\right)+2K(\phi^2+\theta^2)\frac{t^3}{b^3}\right\}$$

(*viii*) $$A_4=\frac{1}{\Delta}\left\{\frac{qr^4}{64F}\left(5+2r\theta\frac{t^3}{b^3}\right)+\frac{r^2K}{2}(\phi^2+\theta^2)\frac{t^3}{b^3}\right\}$$

(*ix*) $$N=\frac{1}{\phi\Delta}\left\{\frac{qr^3}{8F}-\theta K+rK(\phi^2-\theta^2)\frac{t^3}{b^3}\right\}$$

where

(*x*) $$\Delta=2r\theta t^3/b^3+1$$

NUMERICAL EXAMPLE

The linear dimensions of the cylinder and the pressures are those of Dr. Leggett's paper so that a direct comparison can be made.

The material throughout is steel.

The dimensions are as follows:

Mean radius of cylinder	r	0·85 in.
Thickness of cylinder wall	t	0·06 in.
Young's modulus of the material	E	$30\cdot10^6$ lb./in.^{2}
Poisson's ratio	μ	0·25
Thickness of plate	b	0·375 in.
Internal pressure	q	$3\cdot5\times10^3$ lb./in.^{2}
Axial pressure	p	$3\cdot0\times10^4$ lb./in.^{2}
Stress in cylinder wall	σ	$\frac{1}{2}E'\,t\,d^2z/dx^2$
Stress in plate	ρ	$\frac{1}{2}E'\,b\,d^2x/dz^2$
E'		$E/(1-\mu^2)$
Hoop stress	σ_h	
σ_{max}		$7\cdot81\times10^4$ lb./in.^{2}
ρ_{max}		$0\cdot2\times10^4$ lb./in.^{2}
σ_h		$4\cdot95\times10^4$ lb./in.^{2}

If the end circular plate were rigid $\sigma_{max}=8\cdot31\times10^4$ lb./in.^{2}—from Dr. Leggett's results.

CONCLUSIONS

The dimensions of the cylinder and the pressures are such that the flexural stress in the cylinder wall is almost sixty per cent in excess of the hoop stress.

For the same pressures, a thinner plate would cause a reduction in the maximum stress in the cylinder.

The maximum stress in the plate in this particular case is very low.

The cylinders for such mechanisms are not always so simple as the one analysed here. The walls are not usually of constant thickness throughout their lengths, and the circular plate is seldom a plane plate.

The analysis however does show that the stress at the junction of the cylinder and the plate should be investigated.

ACKNOWLEDGMENTS

I am indebted to Dr. D. M. A. Leggett for scrutinising the paper.

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On Running a Machine through its Resonant Frequency

by

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A SOLUTION, in terms of known integrals, is obtained for the motion from rest of a machine, idealised as an undamped linear mass-spring system, when subjected to an exciting force whose frequency varies at a constant rate.

INTRODUCTION

In many installations of modern high speed machinery the running speed of the machine is in excess of the resonant or natural frequency of the system, and consequently starting up or stopping the machine could result in vibrations of large amplitude. The problem of assessing the magnitude and duration of these vibrations is very complicated and has been solved analytically only for the case of a single degree of freedom system excited by an oscillating force whose frequency varies linearly with time[1]. However, even this solution is not easy to evaluate, the integrals involved demanding either graphical construction and numerical integration or summation of series.

The purpose of the present note then is to show how a solution, in terms of previously known functions, may be obtained for the undamped vibrating system. While it is true that this solution is of limited application since damping is always present in practice, in many cases the degree of damping is small and of uncertain magnitude and it is hoped that the comparative ease of solution may outweigh the obvious limitations when a maximum limit to stress, or a minimum allowable acceleration, of a machine is required.

ANALYSIS

For the purpose of vibration study the machine under consideration can be replaced by a mass m and a spring of stiffness k, excited by an oscillating force $Pf(t)$ as shown in Fig. 1, the displacement at time t being x.

Then if the circular frequency of the exciting force is increased from zero at a constant rate a, corresponding to a uniform acceleration of the machine, $f(t)$ may be taken as $\sin at^2$ and the equation of motion of the system is,

$$m\ddot{x}+kx=Pf(t)=P\sin at^2 \quad . \quad . \quad (1)$$

If the displacement and velocity of the mass are zero at time zero, then it is readily verified that the solution of (1) is

$$x=\frac{P}{m\omega}\left(\sin\omega t\int_0^t \sin at^2\cos\omega t\,dt-\cos\omega t\int_0^t \sin at^2\sin\omega t\,dt\right) \quad . \quad . \quad . \quad . \quad (2)$$

where $\omega=(k/m)^{\frac{1}{2}}$ is the natural circular frequency of vibration of the machine.

Equation (2) may be further written as

$$\frac{kx}{P}=\frac{\omega}{2}\sqrt{\left\{\frac{\pi}{2a}(A^2+B^2)\right\}}\sin\ (\omega t-\phi) \quad . \quad (3)$$

where
$$\left.\begin{aligned} A&=2\sqrt{(2a/\pi)}\int_0^t \sin at^2\cos\omega t\,dt\\ B&=2\sqrt{(2a/\pi)}\int_0^t \sin at^2\sin\omega t\,dt\\ \phi&=\arctan\frac{B}{A}\end{aligned}\right\} \quad . \quad . \quad (4)$$

kx/P is the ratio of the instantaneous spring force acting on the mass to the modulus of the driving force, and the motion of the mass is seen to be an oscillation of variable amplitude and of variable frequency.

To obtain the integrals A and B in standard form write equation (4) as

$$A=\sqrt{(2a/\pi)}\left\{\int_0^t \sin(at^2+\omega t)dt+\int_0^t \sin(at^2-\omega t)dt\right\} \quad (5)$$

and put

$$\left.\begin{aligned} y&=\omega\sqrt{\left(\frac{2}{\pi a}\right)}\left\{\frac{at}{\omega}+\frac{1}{2}\right\}=\sqrt{(2/\pi)}\,\Omega\,(\tau+\tfrac{1}{2})\\ z&=\omega\sqrt{\left(\frac{2}{\pi a}\right)}\left\{\frac{at}{\omega}-\frac{1}{2}\right\}=\sqrt{\ (2/\pi)}\,\Omega\,(\tau-\tfrac{1}{2})\end{aligned}\right\} \quad (6)$$

where $\Omega^2=\omega^2/a$ and $\tau=at/\omega$ . . . (7)

Ω is a dimensionless measure of the natural frequency of the machine and its acceleration, while τ is the ratio of the instantaneous forcing frequency to the machine's natural frequency, and when passing through the normal resonance condition τ equals unity.

From (6) and (7) then

$$at^2\pm\omega t=\frac{\pi}{2}\left\{\begin{matrix}y^2\\z^2\end{matrix}-\frac{\Omega^2}{2\pi}\right\}$$

and
$$dy=dz=\sqrt{(2a/\pi)}dt,$$

so that (5) becomes,

$$A=\int_{y_1}^{y_2}\sin\tfrac{1}{2}\pi(y^2-\Omega^2/2\pi)dy+\int_{z_1}^{z_2}\sin\tfrac{1}{2}\pi(z^2-\Omega^2/2\pi)dz, \quad (8)$$

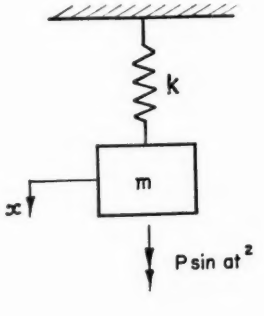

FIGURE 1.

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the limits of integration being

$$\left.\begin{matrix} y_1 \\ z_1 \end{matrix}\right\} = \pm\tfrac{1}{2}\Omega\sqrt{(2/\pi)}, \qquad \left.\begin{matrix} y_2 \\ z_2 \end{matrix}\right\} = \sqrt{(2/\pi)}\Omega(\tau \pm \tfrac{1}{2}).$$

Since the integrands in (8) are identical and are even functions, the lower limits of integration can be combined to give

$$A = \int_0^{y_2} \sin\tfrac{1}{2}\pi(y^2 - \Omega^2/2\pi)dy + \int_0^{z_2} \sin\tfrac{1}{2}\pi(z^2 - \Omega^2/2\pi)dz$$

$$= \cos(\tfrac{1}{4}\Omega^2)\left\{\int_0^{y_2} \sin\tfrac{1}{2}\pi y^2 dy + \int_0^{z_2} \sin\tfrac{1}{2}\pi z^2 dz\right\} -$$

$$- \sin(\tfrac{1}{4}\Omega^2)\left\{\int_0^{y_2} \cos\tfrac{1}{2}\pi y^2 dy + \int_0^{z_2} \cos\tfrac{1}{2}\pi z^2 dz\right\}. \qquad (9)$$

The integrals in (9) are now of standard form and are seen to be Fresnel's integrals[2], which are used, and have been studied extensively, in connection with optics and especially diffraction.

In the usual notation,

$$\left.\begin{aligned} \int_0^u \cos\tfrac{1}{2}\pi t^2 dt &= \mathrm{C}(\tfrac{1}{2}\pi u^2) \\ \int_0^u \sin\tfrac{1}{2}\pi t^2 dt &= \mathrm{S}(\tfrac{1}{2}\pi u^2) \end{aligned}\right\} \quad . \quad . \quad (10)$$

$\mathrm{C}(\frac{1}{2}\pi u^2)$ and $\mathrm{S}(\frac{1}{2}\pi u^2)$ being respectively the Fresnel cosine and sine integral. Therefore

$$A = \cos(\tfrac{1}{4}\Omega^2)\Sigma_A - \sin(\tfrac{1}{4}\Omega^2)\chi_A \quad . \quad . \quad (11)$$

where
$$\Sigma_A = \mathrm{S}(\tfrac{1}{2}\pi y_2^2) + \mathrm{S}(\tfrac{1}{2}\pi z_2^2)$$
$$= \mathrm{S}\{\Omega^2(\tau + \tfrac{1}{2})^2\} + \mathrm{S}\{\Omega^2(\tau - \tfrac{1}{2})^2\}$$
and
$$\chi_A = \mathrm{C}\{\Omega^2(\tau + \tfrac{1}{2})^2\} + \mathrm{C}\{\Omega^2(\tau - \tfrac{1}{2})^2\}. \qquad (12)$$

In a similar manner,

$$B = \sqrt{(2a/\pi)}\left\{\int_0^t \cos(at^2 - \omega t)dt - \int_0^t \cos(at^2 + \omega t)dt\right\}$$

$$= \int_{z_1}^{z_2} \cos\tfrac{1}{2}\pi(z^2 - \Omega^2/2\pi)dz - \int_{y_1}^{y_2} \cos\tfrac{1}{2}\pi(y^2 - \Omega^2/2\pi)dy. \qquad (13)$$

The limits of integration in (13) can once again be combined to give standard forms and

$$B = \cos(\tfrac{1}{4}\Omega^2)\chi_B + \sin(\tfrac{1}{4}\Omega^2)\Sigma_B \quad . \quad . \quad . \quad (14)$$

where
$$\Sigma_B = 2\mathrm{S}(\tfrac{1}{2}\pi y_1^2) + \mathrm{S}(\tfrac{1}{2}\pi z_2^2) - \mathrm{S}(\tfrac{1}{2}\pi y_2^2)$$
$$= 2\mathrm{S}(\tfrac{1}{4}\Omega^2) + \mathrm{S}\{\Omega^2(\tau - \tfrac{1}{2})^2\} - \mathrm{S}\{\Omega^2(\tau + \tfrac{1}{2})^2\}$$
and
$$\chi_B = 2\mathrm{C}(\tfrac{1}{4}\Omega^2) + \mathrm{C}\{\Omega^2(\tau - \tfrac{1}{2})^2\} - \mathrm{C}\{\Omega^2(\tau + \tfrac{1}{2})^2\} \qquad (15)$$

Tables of Fresnel's integrals have been compiled for arguments, $\frac{1}{2}\pi u^2$, up to 50, the most available source probably being Ref. 2. However, since in heavy machines the acceleration will be small, Ω will tend to be large and values of the integrals will be required for large arguments. For values not tabulated the first term of the asymptotic expansions[2] can be used with a high degree of accuracy, giving

$$\left.\begin{aligned} \mathrm{C}(\tfrac{1}{2}\pi u^2) &\sim \tfrac{1}{2} + \left\{\frac{\sin\frac{1}{2}\pi u^2}{\pi u} - \frac{\cos\frac{1}{2}\pi u^2}{\pi^2 u^3}\right\} \\ \text{and} \quad \mathrm{S}(\tfrac{1}{2}\pi u^2) &\sim \tfrac{1}{2} - \left\{\frac{\cos\frac{1}{2}\pi u^2}{\pi u} + \frac{\sin\frac{1}{2}\pi u^2}{\pi^2 u^3}\right\} \end{aligned}\right\} \quad . \quad . \quad (16)$$

From (16) it can be seen that when the argument is large both integrals tend to the value $\frac{1}{2}$, hence if Ω is large and τ has values much greater than unity, the normal resonance condition, then from (11) and (14)

$$A^2 + B^2 \sim 2$$

and so from (3) it can be seen that eventually the system will vibrate at its natural frequency with an amplitude $P\omega\sqrt{(\pi/a)}/2k$. In an actual system, of course, this will not be the case and vibrations initially excited will be damped out.

ACKNOWLEDGMENT

The authors would like to express their thanks to Mr. W. Kirkby of the Structures Department, Royal Aircraft Establishment, Farnborough, for suggesting this problem to one of them (H. McC.). A more detailed and comprehensive study of the whole problem is being undertaken.

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The Motion of an Oscillating Aerofoil in a Compressible Free Jet

by

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THE SUPERSONIC and subsonic jets are both considered by the method used by Miles[1] for an oscillating aerofoil between wind tunnel walls.

The present problem and that of Miles[1] are special cases of the flow past an oscillating aerofoil between porous walls, and provide a useful check for results in the porous wall problem. It may be assumed that the ratio of the change in pressure across a porous wall to the normal velocity at the wall defines a quantity called the porosity parameter, which is a constant at any particular point on the wall. For the special cases of the porosity parameter being everywhere infinite and zero, the porous wall

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corresponds to the solid wall and the free jet boundary respectively.

NOTATION

x, y co-ordinates of a system of axes parallel and normal to the undisturbed flow with origin at the leading edge of the aerofoil
b jet width
c chord of the aerofoil
ρ_0, U, M free jet density, velocity and Mach number
p pressure
ω true frequency of oscillation of the aerofoil
$k=\omega c/U$, reduced frequency parameter
$B^2=M^2-1=-\beta^2$
$y_1=b/(2c)$, non-dimensional half jet width
$A=2By_1$, jet aspect ratio
C_l, C_m lift, moment coefficients
L^{-1} " inverse Laplace transform "
$\operatorname{sgn} y=y/|y|$

Consider an aerofoil of chord c, centrally placed in a free jet of width b, performing simple harmonic oscillations of small amplitude $-U\alpha(x)$ with a true frequency ω. Using linearised theory and making all co-ordinates non-dimensional

$$p(x, y, t)=-\rho_0 U^2 \mathscr{R}\left[\left(\frac{\partial}{\partial x}+ik\right)\phi(x, y)e^{i\omega t}\right] \quad (1)$$

where $k=\omega c/U$ is the reduced frequency parameter and $\mathscr{R}$ denotes " real part of." Since ϕ is antisymmetrical in y the pressure jump across the aerofoil is given by

$$p(x, 0^-, t)-p(x, 0^+, t)=2\rho_0 U^2 \mathscr{R}[\gamma(x)e^{i\omega t}] \quad . \quad (2)$$

where

$$\gamma(x)=\left(\frac{\partial}{\partial x}+ik\right)\phi(x, 0^+) \quad . \quad . \quad (3)$$

Since the pressure is constant on the boundaries of the jet it is seen from Bernoulli's equation that $\phi_x+ik\phi=0$ on the boundaries. This condition is applied at the undisturbed positions of the boundaries *i.e.* $y=\pm y_1$. This is the usual approximation taken in unsteady flow problems and when the jet is considered as a limiting case of flow between porous walls at $y=\pm y_1$ it will have boundaries along $y=\pm y$.

SUPERSONIC JET

The equation of motion for ϕ is

$$B^2\phi_{xx}+2ikM^2\phi_x-k^2M^2\phi-\phi_{yy}=0 \quad . \quad (4)$$

which must be solved subject to

$$\phi_y=-\alpha(x), \quad y=0. \quad . \quad . \quad . \quad (5)$$

$$\phi_x+ik\phi=0, \quad y=\pm y_1. \quad . \quad . \quad (6)$$

$$\phi=0, \quad x\leqslant 0. \quad . \quad . \quad . \quad (7)$$

$$\phi_x=\phi_y=0, \quad x<0. \quad . \quad . \quad . \quad (8)$$

Using the Laplace transform defined by

$$\bar{f}(p)=\int_0^\infty e^{-px}f(x)dx,$$

equations (4) to (8) become

$$\bar{\phi}_{yy}-\lambda^2\bar{\phi}=0 \quad . \quad . \quad . \quad (9)$$

$$\bar{\phi}_y=-\bar{\alpha}(p), \quad y=0. \quad . \quad . \quad (10)$$

$$(p+ik)\bar{\phi}=0, \quad y=\pm y_1, \quad . \quad . \quad (11)$$

where

$$\lambda^2=B^2[(p+i\mathrm{K}M)^2+\mathrm{K}^2] \quad \text{with} \quad \mathrm{K}=kM/B^2.$$

Thus

$$\bar{\phi}=\frac{\bar{\alpha}(p)\sinh\lambda(y_1-|y|)}{\lambda\cosh\lambda y_1}\operatorname{sgn} y \quad . \quad . \quad (12)$$

$$=\bar{\alpha}(p)\,.\,\bar{g}(p, y) \quad \text{(say)} \quad . \quad . \quad (13)$$

By expanding in exponentials $\bar{g}(p, y)$ may be inverted to give

$$g(x, y)=B^{-1}\exp(-i\mathrm{K}Mx)\sum_{n=0}^{\infty}(-1)^n\left\{J_0[\mathrm{K}(x^2-B^2\{2ny_1+|y|\}^2)^{\frac{1}{2}}]\,.\,H[x-B\{2ny_1+|y|\}]-J_0[\mathrm{K}(x^2-B^2\{(2n+2)y_1-|y|\}^2)^{\frac{1}{2}}]\times H[x-B\{(2n+2)y_1-|y|\}]\right\} \quad . \quad (14)$$

where H is the unit step function.

At the aerofoil $y=0$ so (14) reduces to

$$g(x, 0)=B^{-1}\exp(-i\mathrm{K}Mx)\sum_{n=0}^{\infty}(-1)^n\varepsilon_n J_0[\mathrm{K}(x^2-n^2A^2)^{\frac{1}{2}}]\times H[x-nA] \quad . \quad . \quad (15)$$

where $A=2By_1$ is the jet aspect ratio, and $\varepsilon_n=1$, 2 for $n=0$, $n\geqslant 1$.

When $A>1$ the flow at the aerofoil is not influenced by the jet boundaries. The expression arising from $n=0$ is due to an oscillating aerofoil at the origin in a free stream and it is seen that the effect of the jet boundaries could be described by an infinite set of images of alternating sign at $y=\pm 2y_1$, $\pm 4y_1$ . . . . in an infinite fluid.

SUBSONIC JET

In the subsonic case an implicit solution may be found by an argument similar to that employed by Miles[1]. In the present case this Fourier transform method gives

$$\alpha(x)=-\lim_{y\to 0+}\frac{\partial}{\partial y}\int_0^1\phi_1(x-t, y)\gamma(t)\,dt \quad . \quad (16)$$

where $\gamma(t)$ is given by (3),

$$\phi_1(x, y)=e^{-ik\alpha}\frac{\sinh k(y_1-|y|)}{\sinh ky_1}\operatorname{sgn} y-\frac{i\pi}{{y_1}^2}e^{iax}\sum_{n=1}^{\infty}\frac{ne^{-b_n x}\sin[n\pi y/y_1]}{b_n[k+i\beta^2b_n]}, \quad x>0$$

and $\phi_1(x, y)=-\dfrac{i\pi}{{y_1}^2}e^{iax}\displaystyle\sum_{n=1}^{\infty}\frac{ne^{b_n x}\sin[n\pi y/y_1]}{b_n[k-i\beta^2b_n]}, \quad x<0$

with $a=-\mathrm{K}M$ and $b_n=[n^2\pi^2/({y_1}^2\beta^2)-\mathrm{K}^2]^{\frac{1}{2}}$.

SUPERSONIC LIFT AND MOMENT COEFFICIENTS

The lift and moment coefficients may be found, to the first order in k, for a particular prescribed motion of the aerofoil. For a pitching motion of small amplitude α_0 about $x=x_0$

$$\alpha(x)=\alpha_0[1+ik(x-x_0)]$$

and $$\bar{\alpha}(p)=\alpha_0[p^{-1}+ik(p^{-2}-x_0p^{-1})]. \quad . \quad (17)$$

Also, from (3) $$\bar{\gamma}(p)=(p+ik)\,\bar{\varphi}\,(p, 0^+). \quad . \quad . \quad (18)$$

Now $$C_l=4\int_0^1 \gamma(x)dx$$

$$=4\,.\,L^{-1}\{p^{-1}\bar{\gamma}(p)\}\,/_{x=1} \quad . \quad (19)$$

and $$C_m=4\int_0^1 (x_0-x)\gamma(x)dx$$

$$=4\,.\,L^{-1}\{[(x_0-1)p^{-1}+p^{-2}]\bar{\gamma}(p)\}\,/_{x=1} \quad . \quad (20)$$

Therefore,

$$\bar{C}_l=4B^{-1}\alpha_0\left[p^{-2}+ik(p^{-3}-x_0p^{-2})+\right.$$

$$\left.+ikB^{-2}p^{-3}\left(M^2A\frac{\partial}{\partial A}-1\right)\right]\tanh(Ap/2) \quad (21)$$

and $$\bar{C}_m=[(x_0-1)+p^{-1}]\bar{C}_l, \text{ from (17)-(20)} \quad . \quad (22)$$

The inverse Laplace transforms of $p^{-n}\tanh(Ap/2)$, $n=2$, 3, 4, may be found by integrating around the usual contour and summing the resulting series. The results obtained when evaluated at $x=1$ are

$$L^{-1}\{p^{-2}\tanh(Ap/2)\}\,/_{x=1}=A/2+$$
$$+(-1)^m[1-A/2-mA]=h_1(A).$$

$$L^{-1}\{p^{-3}\tanh(Ap/2)\}\,/_{x=1}=A/2+$$
$$+1/2\,.\,(-1)^m[1-mA]^2-A/2\,.\,(-1)^m[1-mA]=h_2(A).$$

$$L^{-1}\{p^{-4}\tanh(Ap/2)\}\,/_{x=1}=A/4-A^3/24+(-1)^mA^3/24-$$
$$-A/4\,.\,(-1)^m[1-mA]^2+1/6\,.\,(-1)^m[1-mA]^3=h_3(A).$$

where $$m<A^{-1}<m+1$$

Writing $$C_l=\alpha_0[l_\alpha+ikl_{\dot\alpha}+0(k^2)] \quad . \quad . \quad . \quad (23)$$

and $$C_m=\alpha_0[m_\alpha+ikm_{\dot\alpha}+0(k^2)] \quad . \quad . \quad . \quad (24)$$

then $$l_\alpha=4B^{-1}h_1(A),$$

$$m_\alpha=4B^{-1}[(x_0-1)h_1(A)+h_2(A)],$$

$$l_{\dot\alpha}=4B^{-1}\left[h_2(A)-x_0h_1(A)+\right.$$
$$\left.+B^{-2}\left(M^2A\frac{\partial}{\partial A}-1\right)h_2(A)\right]$$

and $$m_{\dot\alpha}=4B^{-1}\left[h_3(A)-h_2(A)-x_0(x_0-1)h_1(A)+\right.$$
$$\left.+B^{-2}\left(M^2A\frac{\partial}{\partial A}-1\right)\left(\{x_0-1\}h_2(A)+h_3(A)\right)\right]$$

As already stated, when $A>1$ the boundaries do not affect the flow at the aerofoil and the prediction of the linearised theory for an unbounded stream that the midchord damping derivative $m_{\dot\alpha}$ is positive for Mach numbers in the range $1<M<\sqrt{2}$ is recovered[2].

ACKNOWLEDGMENT

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Rotary Stability Derivatives from Distorted Models

by

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(*A. V. Roe, Canada Ltd.*)

THIS NOTE is presented as an idea to be criticised rather than as a description of a fully developed experimental technique. There are weaknesses in the method which will prevent it from giving absolutely correct answers, for example, the twist imparted to the boundary layer when a body of revolution is rolled cannot be represented. But some of the major effects can be represented, and the idea may possibly be developed to be of practical significance.

It is standard wind tunnel practice to measure the aerodynamic derivatives $C_{Y\beta}$, $C_{l\beta}$, $C_{n\beta}$, $C_{M\alpha}$, $C_{L\alpha}$ and $C_{D\alpha}$ by having a wind stream of constant direction, and measuring aerodynamic forces and moments on a model aircraft placed at angles of yaw and pitch to the stream.

The logical extension of this method, to enable the rotary derivatives to be obtained, is to place suitably distorted models in a wind stream of constant direction. Thus for complete information about one aircraft, four models would be required—one undistorted, one twisted, one curved in the plane of symmetry, and one curved in the normal plane.

By inserting the models at incidence, rotary stability derivatives at incidence in the body axis system could also be obtained by substracting the forces due to incidence (measured on the plane model) from the forces on the distorted model.

Provided that there are no errors in the basic thesis that rotary derivatives can be obtained from distorted models, the method has many advantages over current methods of measuring the derivatives.

(*i*) Inertia effects, such as occur in oscillation techniques, are eliminated, as are acceleration derivatives.

(*ii*) No special tunnel is required, as is the case if curved or rotating flow is used.

(*iii*) The method is readily applicable to transonic or supersonic speeds, as no bulky equipment is required within the tunnel, nor are extra mechanical connections to the outside of the tunnel needed.

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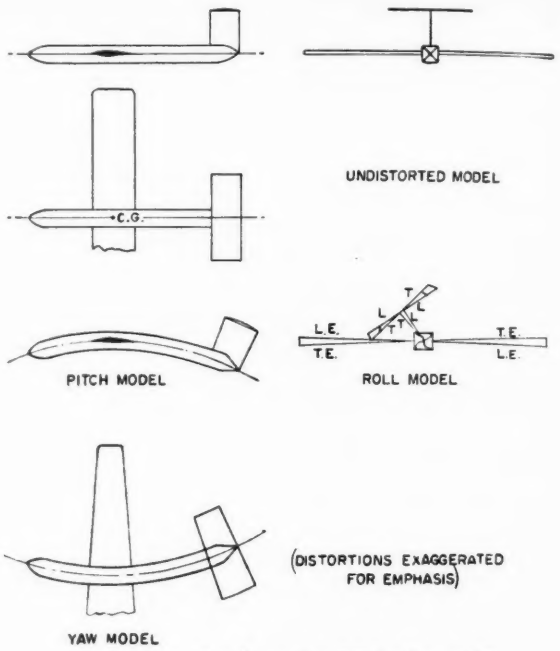
DESIGN OF A DISTORTED MODEL TO YIELD THE ROLLING DERIVATIVES

Consider a model rolling at rate p rads./sec. while flying with speed V ft./sec. A particle of air originally in the plane normal to the axis of the model and containing the model nose will describe a helical path relative to the model, travelling an axial distance x, equal to Vt while moving circumferentially through an angle pt. The same effect is obtained by having a wind stream of velocity V constant in direction and twisting a cross section of the model at distance x from the nose through an angle $\phi(x) = pt = px/V$. The influence of the model may cause the path of the air relative to the model to be other than a true helix, but this effect is of course allowed for automatically by the air having to flow around the distorted model.

Hence the rolling derivatives can be obtained by testing a model which is twisted along its length according to the equation $\phi(x) = px/V$. Note that cross sections normal to the plane of symmetry are undistorted.

DESIGN OF A DISTORTED MODEL TO MEASURE THE PITCHING DERIVATIVES

In a pitching manoeuvre, there is no change of the incidence, the aircraft centre of gravity moving along a circular arc. Consider an aircraft flying horizontally with a velocity V ft./sec., which starts to pitch at q rads/sec. A particle of air orginally in the plane normal to the axis of the model and containing the model nose will move an axial distance x equal to Vt while the angle of inclination of the fuselage reference axis has increased to θ equal to qt. So $\theta(x) = qt = qx/V$, *i.e.*, the centre line of the aircraft is bent into a circular arc in the plane of symmetry of radius R given by $x = R \cdot qx/V$, or $R = V/q$.



Comparison of undistorted and derivative models.

Cross sections normal to the local axis are undistorted. Similarly, in yawing manoeuvres, the plane of symmetry of the aircraft would be curved with radius of curvature $= V/r$.

Graduates' and Students' Section

Mr. K. T. Owen's letter in the August JOURNAL *caused widespread interest. This letter gives the viewpoint of another graduate member of the Society.*

RECENT letters have shown a discontent with the present state of Britain's Aircraft Industry. Two have called on young engineers to show a new spirit and—by implication—laid blame at their door. A third letter stoutly defended young graduates and gave their outlook on the position today.

Why this discontent? Obviously, something is fundamentally wrong. But blaming it on a welfare state outlook by young graduates, as one letter does, can hardly be the answer. It is these self-same graduates who are leaving Britain and its welfare state in increasing numbers for the U.S.A. and Canada. The decision to do this requires the enterprise, enthusiasm and initiative said to be lacking in the youth of today. It is a pity that no effort is made to keep these young engineers in Britain. It is often the best and most able people who go abroad, the clear-thinking ones who assess their future in Britain's Aircraft Industry and decide that it does not hold enough for them.

A letter in the July JOURNAL blames the young engineers of today for not appreciating the fine conditions which have come from the work of their fathers. Its argument is purely on a material level—but I feel that the defects go deeper; many are things of the spirit. But, even on the purely material level, should one be content with a bad state of affairs because a worse one existed yesterday?

It seems to me, after seven years in the Industry, that reforms are needed at two levels. One is material, the other of the mind.

Materially, the trouble lies in the fact that few graduates, despite their many years of training, can expect a reasonable standard of living. They shunt hopefully from company to company, but top-level technical positions are few. The person of average ability may hope to own a car and house and send his children to a reasonable school. He cannot do so. Herein lies one reason, perhaps the main one, for the westbound exodus. In America the average aircraft engineer enjoys a reasonable standard of living. By all accounts he does so in Russia, too.

At least as important as the material side is the attitude of mind of those in industry. At the moment there is a cynicism and lack of confidence. We ended the war with fighters second to none—yet ours today seem nearly a generation behind those of the U.S.A. and Russia. Our bombers are good, but few are in service. Our airliner story is tragic. In a way, we feel responsible—but there seems little urge from above, no stirring call to which we can respond.

In the midst of an international crisis we see factories shut for a fortnight. We see companies advertising for technicians, knowing full well that those they have are not employed to the best advantage. We see no urge or incentive to make an effort. In some cases one feels that aircraft development is not pressed at the speed that the national interest demands.

Such impressions lead to a cynical outlook. This is enhanced by petty restrictions. Technicians are reprimanded if they are a few minutes late—yet they can do a minimum of work and seemingly no one cares. Output of a capstan-lathe operator may be reduced if he starts work five minutes late. Yet who can set a time to creative technical work? Treating professional engineers with suspicion, as though they are not to be trusted, defeats its own ends. Psychologically, it is disastrous. A new outlook, costing not a penny, could make a world of difference here.

In short, my prescription for today's troubles is increased material rewards and, almost more important, a new spirit and outlook at the top of industry. Otherwise, we shall continue to lose the best of our young engineers to other industries and to foreign countries—and we can ill spare them.—G. L. HEARNE, GRAD. R.Ae.S.

AUTUMN LECTURES

A varied programme has been arranged for this autumn; it includes four lectures and a film show.

The first lecture, on 28th September, is on "Novel Methods of Take-off and Landing." It is by Mr. T. J. Cummings, who is with Short Bros. and Harland in Belfast.

On 10th October Squadron Leader P. D. Thorne lectures about "Service Flight-testing of High-speed Aircraft." His experience at Boscombe Down ensures the interest of his talk.

The third lecture—"Nuclear Power for Aircraft"—is by the Chief Executive of the Hawker Siddeley Nuclear Power Company, Mr. E. P. Hawthorne. It will be on 30th October 1956.

On 23rd November Mr. A. W. Kitchenside, of Vickers-Armstrongs, lectures on a subject which is becoming increasingly important today—"The Effects of Kinetic Heating on Aircraft Structures."

A varied programme is planned for the film show to be held on 7th December. Among films to be seen will be ones about the Comet investigation and the Mille Miglia car race.

VISITS

Boscombe Down.—It was most unfortunate that the visit to the Aeroplane and Armament Experimental Establishment at Boscombe Down, planned for Wednesday 29th August, had to be cancelled. There was a hitch in the arrangements which was aggravated by the Hon. Visits Secretary being on holiday for a fortnight, and it proved insurmountable.

A large number of applications were received, several of them from Graduates and Students living in the provinces from whom we hear so little, and it would have been most gratifying if they could have participated in one of our activities. In view of this, it is hoped that a visit may be made at a later date.

National Physical Laboratory.—There may still be some vacancies in the party to visit the N.P.L. at Teddington on Saturday morning, 22nd September 1956. Anyone interested should write to the Hon. Visits Secretary, Mr. N. K. Benson, 14 Wakering Road, Barking, Essex (or telephone RIPpleway 3923 in an evening).

Royal Aircraft Establishment, Farnborough.—A visit has been arranged for Wednesday 17th October 1956 to the Royal Aircraft Establishment, Farnborough, Hants. Would applicants please write **at once** to the Hon. Visits Secretary, Mr. N. K. Benson, 14 Wakering Road, Barking, Essex, stating their grade of membership and nationality. No cameras will be allowed.

R. A. Cole

A happy scene during the Summer Party held recently at 4 Hamilton Place.

THE LIBRARY

Reviews

THE LONELY SKY. *William Bridgeman and Jacqueline Hazard. Cassell, London, 1956. 278 pp. Illustrated. 16s.*

A well known American aircraft manufacturer, on being asked "Howgozit?" anent his latest project is reputed to have replied "Magnificent today—but things will improve tomorrow!". In "The Lonely Sky" we are told just how, during three years of flight testing, things did improve for the Douglas D.558-2 "Skyrocket" research aircraft—from the tests at 300 knots at 16,000 feet which comprised Mr. Bridgeman's first flight in the aircraft to the air drops of the later phases terminating at Mach number of around 1·8 at altitudes of 70,000 feet.

One can have nothing but enthusiasm for this book and admiration for the project with which it is concerned. It gives us the pilot's account of those pioneering supersonic flights about which, up to now, we in Britain have received only bare technical data and the publicity handouts. For this one can forgive the tendency to overdramatisation which is apparent in certain parts of the book and which makes it read, in those parts, almost like a novel. In the descriptions of the flights themselves and the accounts of the behaviour of the "Skyrocket"—including the now-famous "hairy" manoeuvres, a term referring to the violent lateral instability encountered by the D.558-2 at supersonic speed—the book is magnificent. In a very few places, one such being the account of Mr. Bridgeman's first flight in an F.80 "Shooting Star", the prose rises grandly to the occasion and becomes almost poetic.

For a "popular" book the technical details form a large portion of the text and they are, for the most part, accurate. However, one must deprecate in particular the use of phrases such as "half a Mach" to describe speed increments.

This is not so much a biography of Mr. Bridgeman as a technical history of the flight testing of the "Skyrocket", and one feels that on this score it should be required reading for all aeronautical engineers engaged on supersonic aircraft.—J. W. FOZARD.

ACROSS THE HIGH FRONTIER. *W. R. Lundgren. V. Gollancz, London, 1956. 240 pp. Illustrated. 16s. 6d.*

Although there is nothing on the covers or on the title page to inform the reader, this book is the biography of Lt. Col. Charles E. Yeager, U.S.A.F., who, on 14th October 1947, became the first man to exceed the speed of sound. The book is devoted for the most part to an account of the events which led up to this achievement from the time of Yeager's selection, early in 1947, as pilot on the Bell X-1 project when it was taken over by the U.S. Air Force. His wartime experiences as a fighter pilot with the U.S.A.A.F. in Europe during 1944-45 are recounted in a "flash back" which, by comparison with the current biographies of a number of British test pilots, occupies comparatively little of the book.

Odious though it may be, comparison with Mr. Bridgeman's book "The Lonely Sky" is inevitable, and in this respect there can be little doubt that Mr. Bridgeman's book is eminently the more well-knit and readable. Mr. Lundgren, however, takes considerably more trouble to acquaint us with the men who actually designed and built the Bell X-1 than Mr. Bridgeman does for the team behind his Douglas D.558-2. It remains astonishing to be reminded that the basic conception of the Bell X-1 was an accomplished fact as far back as December 1944, and that the first air-launched glide tests of the aircraft took place in January 1946.

One feels that the book falls somewhat between two stools, on the one hand failing to give a full biography of Yeager as a pilot throughout his flying career and on the other hand, by concentrating overlong on the few months preceding the first supersonic flight of the Bell X-1 to the detriment of the later phases of the test programme; it lacks the completeness and the vital interest attained by Mr. Bridgeman's "The Lonely Sky."—J. W. FOZARD.

INTRODUCTION A L'ETUDE DE LA COUCHE LIMITE. *Edmond A. Brun. Gauthier-Villars, Paris, 1955. 189 pp. (In French.)*

This book is an elementary account of Boundary Layer Theory. It is in no sense a book for the scholar and gives no references to original or other work at all. It deals only with two-dimensional flow, and the standard it sets may perhaps be judged from the fact that the full Navier-Stokes equations of motion are nowhere mentioned.

Nearly all the analytical methods quoted in the book are derivations from the momentum equation of Boundary Layer Flow, but even in this the book is not up to date, the most recent simplifications of the theory of the momentum equation not receiving a mention. The mathematics, therefore, need cause no-one's hair to stand on end, and it is for this reason that possibly many people might find a use for an elementary account which does give a good idea of what is happening in practice in boundary layers along two-dimensional surfaces.

A virtue of the account is that it gives due weight to thermodynamic phenomena and it does not confine itself to laminar flow. The facts of turbulence are discussed. It is therefore a beginner's book, and for a beginner moreover whose French is fluent, for otherwise it would not be worth buying.—BRYAN THWAITES.

GEOGRAPHIE DE LA CIRCULATION AERIENNE. *Eugène Pépin. Gallimard, Paris. 341 pp. Illustrated. 1200 francs. (In French).*

The foreword by Dr. Edward Warner is in itself an assurance that this book is of definite value. The first part consists of a general history of the development of aviation, including some items not commonly found in such works. This is followed by a general survey of each of the main aspects of present-day commercial aviation and a glimpse into future possibilities. Navigational aids, meteorology, International Legislation, Air Traffic Control, airport organisation, aircraft types, and other aspects are all briefly covered.

The book is preceded by a list of abbreviations which is not entirely accurate and is not rigidly followed in the main letter press. The useful bibliography is divided into sections in the same way as in the main work, making for easy reference. A good index is provided, but more careful proof-reading seems to have been needed in the non-French names; for example, the name of the Lockheed Company is spelt in at least three fashions.

On the whole this is a generally accurate survey of civil aviation up to the end of 1955. It can be regarded as a useful source of information for popular types of lecture, but not for very advanced work.—R. F. BULSTRODE.

THE VIKING ROCKET STORY. *By Milton W. Rosen. Faber and Faber. London, 1956. 248 pp. Illustrated. 21s.*

The author of this book was appointed last year to be Technical Director of the American "Vanguard" Earth Satellite project, the programme for which calls for ten rockets to be launched into their orbits during the forthcoming (1957-58) International Geophysical Year. He is also a director of the American Rocket Society, and Chairman of its Space-Flight Committee.

At the close of the war, he was a physicist working on radio and radar devices for the U.S. Naval Research Laboratory in Washington. In 1945, he had come to be engaged on control and guidance problems for missiles, and so to be involved in discussions on the projects which the U.S. Navy should sponsor for rockets and other weapons of this kind. His own proposal was for an ambitious research vehicle which, while giving valuable experience in the design, development and operation of large rockets, would also enable scientists to gather vitally important data on the extreme upper atmosphere. It was adopted, and he was put in charge of it on behalf of the Navy.

The rocket was in due course called the Viking, and Rosen's book, as aptly indicated by its title, is its story, and that of the men who built and fired it. It is a most readable account, well written in a generally restrained style but not going into any great technical detail, and only slightly marred by some undue repetition of the "X minus 10 minutes . . . . 5-4-3-2-1 — Fire!" business, so beloved now by the film fraternity. Of other adverse criticism, one could fairly say little more but that some of the popular explanations of rocket functioning, and so on, although very well done, are superfluous for the readers who will find the book of greatest value and interest.

These should undoubtedly be found among all those concerned in any way with the development of advanced rocket projects of any sort. The Viking story has a happy ending, for this largest of all pure research rockets to be fired so far eventually gained the altitude record for which it was built and so secured very valuable research data. However, before success was attained, a period of great tribulation ensued for all concerned, and Rosen tells the tale of all this with commendable and very informative frankness, teaching a lesson to all of us who are faced with similar problems.

Valves seized up, leaks developed, strange vibrations appeared, firings failed to take place on schedule and the constant postponements and delays generated the inevitable following of sceptics and fun-pokers. Performances invariably tended to fall short of the theoretical predictions. Vikings 1 and 2 cut their own power prematurely and reached only a fraction of their intended heights; Viking 3 was deliberately cut off, with the same result, because its trajectory was not developing as planned. However, Viking 4 (launched from a ship, on the equator) exceeded 100 miles, and so did No. 5. After this, the return to the White Sands proving ground in New Mexico brought more disappointment; the fins of No. 6 collapsed in flight, resulting in some unpremeditated aerobatics and a height of only 40 miles once again. Then, No. 7 at last attained 136 miles, higher than the competitive V-2, and much closer to the specification figure.

Viking No. 8 was the first of a re-designed series, with improved mass ratio and greater propellant capacity. It achieved the distinction of reaching the greatest height (4 miles) ever attained on a "static" test, for it broke loose during a "pre-flight" check firing. However, No. 9 again got to 135 miles, after which No. 10 suffered a "hard start"; its motor exploded, a serious fire developed, and the missile had to be re-built before it, too, reached 136 miles. No. 11 was the record-breaker, with 158 miles, and No. 12, with 144 miles, also behaved in such a way that the project team were encouraged in the belief that their struggles were at last being crowned with well-deserved success.

Two more Vikings remained to be fired; the development described here and in the book extended all the time from May 1949 to February 1955. At least by trans-Atlantic standards, the Viking programme was not backed by lavish funds and high priorities but more nearly on the scale we are accustomed to over here. We may expect to see faster progress with the American and Russian I.C.B.M.'s and I.R.B.M.'s, in no small measure because of the experience gained with such research projects as Viking. Those who are engaged on such projects in the United Kingdom would do well to read Rosen's book and ponder its moral; these things are not easy, and one must not give up too soon or expect results too quickly and cheaply.

Certainly Rosen and his group, the Glenn L. Martin Co. (who built the Viking) and Reaction Motors, Inc. (who built its 20,000 lb. thrust engine), all deserve the highest praise for their able and tenacious striving. To end on a note both personal and technical: those who, like this reviewer, have worked with hydrogen peroxide, will find Rosen's references to this useful fluid decidedly irritating and inaccurate; we are told that it is "explosive", difficult and dangerous to store, transport, and handle, and that "one drop on a man's skin could cause a painful and slow-healing burn"—which latter statement, in particular, is utter nonsense. Untrue as all these things are, no doubt Rosen quotes them in all sincerity, but his own account refutes them. He has no peroxide "incident" to report; when the power plant bay of Viking 10 was ablaze, the peroxide tank did *not* explode and he tells us that, when supplies ran short on one occasion, two realistic Martin engineers loaded a 50-gallon drum in the back of a station wagon and just drove it 2,000 miles from Buffalo down to White Sands.—A. V. CLEAVER.

THE CENTRAL BLUE. *Recollections and Reflections. Marshal of the Royal Air Force Sir John Slessor, G.C.B., D.S.O., M.C. Cassell, London, 1956. 709 pp. Illustrated. 30s.*

Sir John Slessor's recollections are not brought down to the post-war years. They end in 1945. The part he played in securing acceptance of the policy of deterrence still remains to be described. What he did to work out its implications in terms of equipment, training and strategy will perhaps have to remain secret until the next generation of bombers, the supersonic fore-runners of the promised "inter-continental ballistic missiles," is in service. His forthright views on the atomic bomb have been made known in another publication. His present fat volume of autobiography shows both how well-equipped he was as a negotiator to advise his political masters and how fortunate the nation was at a time of revolution in defence conceptions to have as Chief of Air Staff one of the most articulate of its senior officers.

In this book he declares that he has never been able to think clearly except with a pencil in his hand. His book bulges with evidence that he can indeed think clearly in writing but all his friends, and especially such as have occasionally prodded him into indignation, will testify also to his liveliness and pungency in handling the spoken word. Once, at least, he confesses his enjoyment of an hour of expounding to one of the best listeners in the world, the

late F. D. Roosevelt. He must likewise have had a happy hour with the redoubtable Admiral Ernest J. King in 1943 on the subject of anti-submarine co-operation although he got little change out of this ultra-American chief who " barely acknowledged Coastal Command's existence " and whose obsession with the Pacific " cost us dear in the Atlantic." Unhappily his recollections hardly extend to conversations, except for the odd anecdote or the report of a fatuous comment from the highly-placed. The written word holds the stage and has the advantage, of course, of being irrefutable.

This makes his book extremely " meaty " and the historian will give it a warm welcome on this account, for the author in his steady climb up the promotion ladder was as much engaged in staff duties as in command and saw most of the game from the inside, sharing in the various struggles with the Army, the Navy, the French, some of the Americans and some of the politicians. It might also have been heavy but for the zest with which all his work was done and for his relative inability to remain dumb and inactive when a point of view needed to be put forward or the appreciation of a situation needed to be made. Initiative breaks out in him like a rash and with it goes a splendid self-confidence fortunately backed by good judgment which made him as fully capable of saying " No " to impossible demands as of pressing with all his power for the realisation of desirable ends.

Snorts of disgusted impatience at the folly of those who ought to have known better give his book a strength and honesty typical of one side of this capable and hard-working strategist and tactician—at Gamelin in 1940 for his distrust of air power, at Ironside for the hazy language of some of his opinions, at those soldiers who in 1940 said: " We are relying on the air to stop the Germans," at the short-term expedients of a Beaverbrook and the bland obstructionism of an Ernest J. King, even at the bluster of a Patton whose attitude on arriving at Norfolk House in 1942 was: " Stand back and let the dog see the rabbit. What the hell's all this goddam planning? Where's the enemy? Why don't we get going?" And yet that is only one side of the man, betraying not intolerance but an irrepressible devotion to truth, efficiency and sound policy. His admiration for most of the people he had to deal with, his obvious liking for his fellow men and the ease of his social contacts explain why he was as good in Bomber Command and as C.-in-C. Coastal Command as he was in Whitehall or Washington.

No doubt too much has gone into this book to allow it to remain readable in the entertainment sense. Its very documentation, proving cases beyond argument, is something of a deterrent to all except the serious students of air history and because of the documentation there is some repetition so that " skipping " by the reader tends not to be the crime the author might consider it. Not even the skipper is likely to remain unaware of the author's principles or of his phobias, as for examples on aircraft-carriers or the tying of air units to Army formations or the use of the bombers as a " battlefield weapon " or airborne troops (except for special purposes) or naval designs on Coastal Command. Nor is he in danger of underestimating the author's ineradicable distrust of Russia and contempt for her cynical policies. Even that could not move him from his realistic appraisal of possibilities when he was under pressure to send aid to the tragic rising in Warsaw in 1944. It certainly had its influence in his post-war advocacy of the " deterrent force."

A large part of his merit as a staff officer belonged plainly to the breadth of his interests in nations and affairs and men and life. The big things and the little come tumbling into his book equally alive and shown as equally evocative of the best a man can give. Take for instance that belief of the bomber crews in 1941 that beer bottles pitched overboard could fox the searchlights. He called in a boffin and perhaps gave birth to " window." At the other end of the scale, in Washington in 1940, he could pester the powers in Whitehall for all the facts and figures caution would have withheld and without which America could not have been persuaded to " give us the tools " in adequate quantities. This conception of the essential unity of the Air Force officers' job whether in command or on the staff or as the negotiator of joint plans is one of the valuable impressions left by this book. In addition, except for the documents, its style puts the man himself on the pages, his accents and idioms, often colloquial and generally forceful, bringing him whole to the reader's ear as well as eye. It is a book well worth wading through.—E. COLSTON SHEPHERD.

MATHEMATICS OF ENGINEERING SYSTEMS. *Derek F. Lawden. Methuen, London, 1954. 380 pp. Diagrams. 30s.*

This is a textbook of mathematics written by a mathematician. It is, however, the mathematics of the control systems engineer. The author himself has had much first-hand experience of such systems at the Royal Military College of Science. He has also lectured to engineers and prospective engineers for many years. Thus it is not surprising that this book meets the needs of the engineer wishing to enter design, development or research projects in automatic control problems. Throughout the book, physical and practical examples of the equations being studied are given, and there are also a large number of problems for the reader to attempt himself, with some hints and the correct answers collected at the end.

The book is basically divided into four sections, not including a 53-page introduction of fundamental elementary ideas in revision form. The first section deals with the solution of problems concerned with " linear " systems and using only classical ideas of solving differential equations. The next gives an extension of these ideas using the more modern but universally accepted operational methods involving Laplace Transforms. This latter section also develops the harmonic analytical techniques so favoured by the control engineer and includes the Nyquist criterion of stability. This is placed in a proper perspective by a general study of stability criteria. Typical of the examples considered in this section is that of a second order position control system with an additional constant line delay.

The third section is concerned with harmonic analysis. Fourier series for periodic and non-periodic waveforms are dealt with at length, followed by the development of Fourier integral equations and the concept of frequency spectra. The extension from series to integrals is particularly nicely presented. The last section deals with hte various methods available for extracting information from non-linear differential equations. The phase-plane technique with Lienhard's graphical construction, perturbation methods and linearisation methods are dealt with adequately. This non-linear section will probably be regarded as the most important of the whole text in view of the increasing awareness of the need for study of non-linear effects in control systems.

For a mathematical text, the book is well written, making it easy to follow. The type-setting of the equations is also good. The book fills a need and will be useful to anyone concerned with automatic control problems.—J. C. WEST.

MATHEMATICAL THEORY OF ELASTICITY. *I. S. Sokolnikoff. Second Edition. McGraw-Hill, New York, 1956. 476 pp. 73 diagrams. $9.50.*

The main difference between the first and second editions of this well-known book lies in the addition of two substantial and completely new chapters—one on "Two-Dimensional Elastostatic Problems," the other on "Three-Dimensional Problems." The former chapter is particularly important as it makes good what was felt to be rather a serious omission from the first edition, namely a really good and applicable account of the complex variable methods which have recently become available for solving two-dimensional elastic problems.

There is no doubt that the new material contained in the second edition will considerably enhance the value of what has already come to be regarded as one of the standard works on elasticity.—D. M. A. LEGGETT.

PRACTICAL SOLUTION OF TORSIONAL VIBRATION PROBLEMS. *VOL. I. FREQUENCY CALCULATIONS. W. Ker Wilson. Chapman and Hall, London, 1956. 704 pp. Illustrated. 105s.*

Dr. W. Ker Wilson's book appeared first in 1935 and a second edition was published in 1940 in two volumes. That a third (revised) edition has now been produced emphasises the importance both of the book and of its subject. The complete work remains in two volumes; but it has been completely rewritten and brought up to date and the presentation has been re-arranged so as to make each volume self-contained.

The chapter headings of the new Vol. 1 are as follows: Simple Systems; Frequency Tabulations; Multi-Mass Systems; Simple Geared Systems; More Complicated Geared Systems; Coupling Effects in Geared Systems; Effective Inertia Method—Concentrated Mass Systems; Effective Inertia Method—Distributed Mass Systems; Coupled Torsional and Flexural Vibration in Engine Systems; Equivalent Masses; Equivalent Shafts; Official Requirements Relating to Vibration. There is, in addition, a long list of references. Those who are familar with this book (and they are many) will realise that this list indicates a complete overhaul of the layout of Edition 2. The change is certainly for the better and the author's lucid style and taste for detail is not lost.

As its title implies, this book deals with a particular aspect of vibration. Within this limitation, it is undoubtedly a work of the greatest importance. In dealing with his subject, the author adopts a down-to-earth approach and the adjective *practical* is very properly incorporated in the title.

If the book has a shortcoming it is that, so great is the emphasis laid upon the solution of *torsional* problems, little attention is paid to other aspects of vibration theory. The result is that this book is more of a work of reference than a textbook. It is perhaps hardly fair to criticise the author for this however. He has chosen his subject and he has stuck to it; in doing so, he has decided not to devote much attention to the fact that torsional vibration is just a particular form of oscillatory motion. For a book of this sort, the decision is possibly a wise one.

The Royal Aeronautical Society's reviewer of the Second Edition (Journal, Vol. 45, p. 231, 1941) drew attention to the excellence of the book as an example of the printer's art. He was right, and the standard has been maintained. He also drew attention to the high price, which was then two guineas per volume. The volume now under review costs five, but it will still be regarded as an excellent investment by those who are concerned with torsional vibration problems.—R. E. D. BISHOP.

THE ECONOMICS OF EUROPEAN AIR TRANSPORT. *Stephen Wheatcroft. Manchester University Press, 1956. 358 pp. Diagrams. 35s.*

European short-haul airlines have to be considered in their own capacity, not as feeders to other routes. Their work should be tested against the cannons of economic rationality first, only second against the requirements of national interest. On the basis of these two assumptions, perhaps natural to a trained economist in the service of B.E.A., the author has supplied us with a triumphant vindication of basic B.E.A. policy, as well as a great deal of thoughtfully organised information about the European airlines. Over-water routes continue to be of basic importance to the pattern of these lines, even though each in itself is in the form of spokes radiating from a national capital as hub. In terms of passenger rates, there are essentially three kinds of European air route: Continental, U.K.-Continental and North-South (to Scandinavia). Rates depend primarily on the competition experienced with alternative surface transportation. With the gradually declining fares of 1947-53, little apparent elasticity of demand appeared: steady and spectacular increase in air traffic seemed to be remarkably independent of small changes in rates. Could Wheatcroft's characterisation of European air travellers as "discriminating" be even more true than he thinks? The argument that small price changes mean little to the people who do most air travelling, could not, however, be pushed to full advantage in this book. While the author believes in the lowest fares economically possible, he realises that the existing international system of fixing rates will not withstand sudden, large tariff reductions, and he hopes not only to retain but to expand international co-operation among airlines.

His informed advocacy of large, fast, flexible aeroplanes for use on the short hauls (200-500 miles) is convincing. He builds an unimpeachable argument for maintaining traffic at the most intense level possible. But his essay into the relationship of airline size and efficiency is somewhat barren. His study of the published figures for fourteen American airlines led him to conclude that there are no further economies of scale to be had at levels of annual airline production above 150 million capacity ton miles. But there are apparently no dis-economies to be encountered, either. Some of the most efficient American lines are among the largest; and only two tiny airline companies are shown to be conspicuously less efficient than the general run. At best, Wheatcroft proves that variation in size has little to do with efficiency, above an extremely low limit. Nevertheless, Mr. Wheatcroft's work will truly serve us, as Peter Masefield says in a Foreword. It is a useful compendium, the book with which one must now contend before attacking the manifold "economic" problems of air transport in Europe.—H. J. HAGEDORN.

BORN TO FLY—EXPLOITS OF THE WAR'S GREAT FIGHTER ACES. *Georges Blond. Souvenir Press, London, 1956. 208 pp. Illustrated. 16s.*

This is a train-journey book and the sub-title tells you just what to expect. There are pilots of whom the reader has never heard and there are names omitted that will provoke every reader to say, "Why on earth has so-and-so been left out?" Cunningham, of course, is a safe choice and nobody will quarrel with George Beurling's inclusion. Perhaps it is just one's unfamiliarity with the heroes of other nations, and therein is a virtue of the book. It has a representative from nearly every nation which participated in the last war and friend and foe alike are judged

on their merits as fighting men. One does not expect books like these to be serious contributions to biography but the author presents a very readable book.—F.H.S.

WORLD AIRCRAFT RECOGNITION MANUAL. *C. H. Gibbs-Smith and L. E. Bradford. Putnam, London, 1956. 269 pp. Illustrated. 15s.*

One subject on which it is difficult to get any two librarians to agree is that of "classification". I suspect that a similar position must arise with writers of aircraft identification works. Messrs. Gibbs-Smith and Bradford plump for wing-shape which is, one supposes, as good as any. The divisions are delta, swept, straight and rotary. These divisions are again grouped according to their "visual characteristics" — number of engines, wing position, etc. Luckily for those who simply wish to know what a particular aeroplane looks like and what makes it go, there is an excellent index. Mr. Gibbs-Smith contributes a "Short Introduction to Recognition Training" in which he combines the techniques of Sherlock Holmes and Rapid Reading. But why have the authors spread themselves with three views plus silhouettes of some aircraft and provided only one photograph (of doubtful use in identification) of others?—F.H.S.

ROCKETS AND SPACE TRAVEL. *M. F. Allward and J. W. R. Taylor. Ian Allan Ltd., 1956. 64 pp. Illustrated. 3s.*

This latest addition to the well-known Ian Allan ABC series differs somewhat from its predecessors in content. There are not enough rockets to fill an identification book but it is extremely convenient to have the Vikings and the Corporals and the Nikes listed with their available data so that one can tell if one is thinking of an air-to-air or a ground-to-air and so on. An informative little article on the history of rocketry precedes the usual ABC layout and the last 20 odd pages are devoted to astronautical articles—what has been achieved and what might be done in the future.—F.H.S.

PASSENGERS PARCELS AND PANTHERS. *J. W. R. Taylor. Dennis Dobson Ltd., 1955. 159 pp. 10s. 6d.*

This book describes briefly not only the sort of aviation that is generally known, but also the less publicised. Chapters such as "Flying the Mail," "Flying Doctors," "Camera in the Clouds" are self-explanatory, but "Down on the Farm" and "Beans, Beds and Bulldozers" may need a little explaining. The former deals with such jobs as crop-spraying and fertilising, while the latter is an alliterative reference to the various types of cargo that are now being flown all over the world. "Flying Zoos" shows that aeronautical progress has now gone full circle. This is not a technical book but it is very readable: interesting to adults and youngsters.—F.H.S.

AIRCRAFT YEAR BOOK 1955 (*Official publication of the Aircraft Industries Association of America Inc.*). *F. Hamlin and E. T. Miller, Editors. Lincoln Press, 1956. 477 pp. $6.*

This is the 37th annual edition of a handbook that has maintained the same high standard throughout its life. It is difficult to describe its exact usefulness but the present writer has found it a mine of useful information about the American industry, especially in dealing with sweeping questions about the "present position of aircraft in the States." It represents, says the "Acknowledgements" the "combined editorial talent of the industry." The result is an authoritative and informative reference book to all branches of the industry.—F.H.S.

Additions to the Library

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** Items marked thus are for reference use only.*

Reports

AERODYNAMICS

Boundary Layer

Some problems in boundary-layer transition. J. A. Steketee. UTIA Report No. 38. (*April* 1956).

A few models are explored with perturbation procedures as it has not been possible to formulate the problem in clear mathematical terms. It is believed that the investigation throws some light on the importance of the velocity gradient of the mean flow for the phenomena observed.—(1.1.2.1).

Méthodes de calcul de la couche limite laminaire bidimensionnelle en régime compressible. E. A. Eichelbrenner. O.N.E.R.A. Publication No. 83. (1956).

Après avoir exposé trois méthodes (globale, à différences finies, hodographique) de calcul de la couche limite laminaire bidimensionnelle en fluide compressible, on soumet les conditions initiales à une étude critique visant particulièrement le problème de la couche limite derrière une onde de choc détachée dont on discute ensuite les difficultés mathématiques.—(1.1.1.4).

Exact solutions of laminar-boundary-layer equations with constant property values for porous wall with variable temperature. P. L. Donoughe and J. N. B. Livingood. N.A.C.A. Report 1229. (1955).

Solutions were computed for a Prandtl number of 0·7 and a range of cooling-air flows, and pressure and wall temperature gradients. For each case, boundary layer thicknesses and heat-transfer and friction coefficients were also computed and tabulated.—(1.1.1.1 × 1.9.1).

An investigation of the effects of heat transfer on boundary-layer transition on a parabolic body of revolution (N.A.C.A. R.M.-10) at a Mach number of 1·61. *K. R. Czarnecki and A. R. Sinclair. N.A.C.A. Report* 1240. (1955).

The effects of heat transfer on boundary layer transition on a parabolic body of revolution (N.A.C.A. R.M.-10) were investigated. The tests were made at a Mach number of 1·6 and over a Reynolds number range from $2{\cdot}5\times10^6$ to 35×10^6. A comparison is made between the experimental results and theory.—(1.1.2.4 × 1.9.1).

Boundary layer. L. G. Loitsianskii. N.A.C.A. T.M. 1400. (*May* 1956).

The scope of papers on boundary layer contained in seventy references for the period from 1917 to 1948 are reviewed.—(1.1).

Boundary layer behind shock or thin expansion wave moving into stationary fluid. H. Mirels. N.A.C.A. T.N. 3712. (*May* 1956).

The boundary layer behind a shock or thin expansion wave moving into a stationary fluid has been studied. Both laminar and turbulent boundary layers were considered. The wall surface temperature behind the waves was also investigated.—(1.1.1.4 × 1.1.2.4).

Compressible Flow

Some tests on the spread of velocity in a cold jet discharging with excess pressure from a sonic exit into still air. J. Seddon and L. Haverty. C.P. 246. (1956).

The spread of the half-velocity circle in a jet discharging with excess pressure from a length of parallel pipe into still air has been examined over the range 40 to 200 diameters from the exit. Jet pressure ratios (outside static pressure + jet total pressure) were from 0·479 to 0·042, corresponding to isentropic Mach numbers from 1·08 to 2·72.—(1.2.3).

Unsteady supersonic flow. John W. Miles. Air Research and Development Command. (*March* 1955).

The monograph is intended to survey the application of the theory of perfect fluid flow to the prediction of the aerodynamic forces that act on thin wings and slender bodies as a result of small, unsteady motions with respect to an equilibrium configuration of uniform, supersonic flight. In addition, certain aspects of the corresponding subsonic problem are taken up in so far as they afford informative comparisons with their supersonic counterparts.—(1.2.3.1 × 1.10.1.2).

On the range of applicability of the transonic area rule. J. R. Spreiter. N.A.C.A. T.N. 3673. (*May* 1956).

Some insight into the range of applicability of the transonic area rule has been gained by comparison with the appropriate similarity rule of transonic flow theory and with experimental data for a large family of rectangular wings having N.A.C.A. 63AXXX profiles.—(1.2.2.1 × 1.10.2.2).

Comparison of the experimental and theoretical distributions of lift on a slender inclined body of revolution at M=2. E. W. Perkins and D. M. Kuehn. N.A.C.A. T.N. 3715. (*May* 1956).

An investigation of the pressure distribution for a body of revolution, consisting of a 33½ calibre (5·75 fineness ratio) tangent ogival nose and a cylindrical afterbody, has been made for an angle of attack range of 0° to 35·5° at a Mach number of 1·98 and a Reynolds number of approximately $0{\cdot}5\times10^6$, based on body diameter.—(1.2.3.1).

Comparison of experimental and theoretical normal-force distributions (including Reynolds number effects) on an ogive-cylinder body at Mach number 1·98. *E. W. Perkins and L. H. Jorgensen. N.A.C.A. T.N.* 3716. (*May* 1956).

Effects of Reynolds number and angle of attack on the pressure distribution and normal force characteristics of a body of revolution consisting of a fineness ratio 3 ogival nose tangent to a cylindrical afterbody 7 diameters long have been determined. The test Mach number was 1·98 and the angle of attack range from 0° to 20°. The Reynolds numbers, based on body diameter, were $0{\cdot}15\times10^6$ and $0{\cdot}45\times10^6$. The experimental results are compared with theory.—(1.2.3.1).

Control Surfaces

Some wind-tunnel experiments on single-degree-of-freedom flutter of ailerons in the high subsonic speed range. S. A. Clevenson. N.A.C.A. T.N. 3687. (*June* 1956).

Results of tests of three wing models with various aileron configurations are presented.—(1.3.1 × 2).

Internal Flow

Flat plate cascades at supersonic speed. R. M. El Badrawy. N.A.C.A. T.M. 1369. (*May* 1956).

A brief review of exact two-dimensional supersonic flow theory and Ackeret's linearised theory are first presented. The lift and drag coefficients of a cascade of flat plates are calculated exactly and compared to those obtained using the linearised theory.—(1.5.4.1).

Flow of gas through turbine lattices. M. E. Deich. N.A.C.A. T.M. 1393. (*May* 1956).

This report is concerned with fluid mechanics of two-dimensional cascades, particularly turbine cascades. Methods of solving the incompressible ideal flow in cascades are presented.—(1.5.4.3).

Loads

See also Wings and Aerofoils

Preliminary low speed wind tunnel tests on flat plates and air brakes: flow, vibration and balance measurements. R. Fail. et. al. C.P. 251. (1956).

Flow measurements have been made behind sharp edged flat plates: (*a*) at 90° for various shapes, and (*b*) for a square plate over an incidence range. Lift, drag and pitching moment increments were measured on a square plate mounted on (*a*) a long cylinder and (*b*) near the end of several shapes of rear fuselage.—(1.6.3).

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

INSTRUMENTS AND EQUIPMENT

A miniature eight-channel pressure recorder. G. A. Parker. A.R.L. Note 1.57. (*January* 1956).

An eight-channel pressure recorder is described, its development is traced and instructions for the user are appended. The stylus-on-celluloid method of recording is used as this allows a great deal of information to be accurately recorded on a small area of recording medium. —(18).

MATERIALS

See also SCIENCE—GENERAL; STRUCTURES—THEORY AND ANALYSIS

*A highly sensitive gauge for the measurement of large strains. A. G. Boyer and J. P. O. Silberstein. A.R.L. Note SM.*221 (*October* 1955).

The exploration of the physical laws governing the behaviour of metals under high stress requires the measurement of strains of more than 5 per cent. to an accuracy of at least one part in a thousand. A gauge was designed and developed to meet this requirement. It is in the form of an arch and has electric resistance strain gauges attached to it at the top of the arch.—(21.6.2 × 33.3.1).

The flexural fatigue properties of spin dimpled 75 *S-T aluminium alloy sheet. D. Donelly and J. M. Finney. A.R.L. Note SM.*222 (*October* 1955).

Flexural fatigue tests were made on unnotched, spin dimpled and drilled hole specimens using 75 S-T aluminium alloy sheet. Comparison with previous tests on hot and cold coin dimpled specimens showed that, at 10^5 cycles, there was no appreciable difference in fatigue strengths but that at 10^7 cycles the spin dimpled specimens were 17 per cent stronger than the cold coin dimpled specimens and 4 per cent weaker than the hot coin dimpled specimens.—(21.2.2).

*Some preliminary tests on sandwich face and core materials. N.L.L. Report S.*336. (1948).

Tests were made on a few small samples of Dufaylite and Calcium Alginate core materials to determine the moduli of rigidity. Further preliminary tests were made on a sample of Holoplast face material to evaluate both moduli of rigidity and elasticity.—(21.3.6).

*Shear and tensile tests on sandwich core materials. N.L.L. Report S.*350. (1949).

Further to the preliminary tests mentioned in N.L.L. Report S.366 more frame shear tests were carried out on specimens fabricated from Balsolite, Calcium Alginate and Onazote core materials to evaluate the modulus of rigidity for transverse shear. Tensile tests were also made on specimens of Onazote material to obtain data on the elastic modulus in tension perpendicular to the sandwich face-plates.—(21.3.6).

Effect of crack length and stress amplitude on growth of fatigue cracks. W. Weibull. F.F.A. Report 65. (1956).

Earlier observations have indicated that the growth rate of a fatigue crack, which in usual fatigue tests with constant load amplitudes rapidly increases with the length of the crack, would be constant if the stress amplitude were kept constant, *i.e.*, that the observed increase of the rate is entirely due to the increase in stresses caused by the decreasing cross-sectional area. To verify this assumption, fatigue tests with notched specimens of unclad 24 S-T and alclad 75 S-T sheets have been run with nearly constant stress amplitudes, obtained by reducing the load in proportion to the remaining area.—(21.2.2).

Investigation of the Ni_3Al phase of nickel-aluminum alloys. E. M. Grala. N.A.C.A. T.N. 3660 (*April* 1956).

An investigation was made to determine the effects of homogenisation treatments and of composition on the tensile properties of as-cast alloys in the Ni_3Al-intermetallic-phase region.—(21.2.2).

Influence of alloying upon grain-boundary creep. F. N. Rhines, et al. N.A.C.A. T.N. 3678 (*April* 1956).

Grain-boundary displacement, occurring in bicrystals during creep at elevated temperature (350°C), was measured as a function of the copper content (0·1 to 3 per cent.) in a series of aluminium-rich aluminium-copper solid-solution alloys. Because alloying effects alone were to be investigated, the conditions of observation were limited to a single temperature and range of stress.—(21.2.2).

Investigation of plastic behavior of binary aluminum alloys by internal-friction methods. R. E. Maringer, et al. N.A.C.A. T.N. 3681. (*June* 1956).

The relationship between internal friction and plastic deformation in binary aluminium alloys was investigated, with the percentage of alloying element taken as a variable parameter. The effects of strain rate, amount of strain, heat treatment, temperature, and testing frequency on internal friction during plastic deformation were also studied. The experimental observations are analysed in light of modern dislocation theory.—(21.2.2).

MATHEMATICS

On the instability of methods for the integration of ordinary differential equations. H. Rutishauser. N.A.C.A. T.N. 1403 (*April* 1956).

In the numerical solution of a differential equation as a difference equation, the latter is usually of higher order and therefore has more solutions than the original differential equation. It may well be that some of these "extra" solutions grow faster than any solution of the given equation; in this case the computational solution has the tendency to follow one of these and has, after a certain number of integration steps, nothing to do with the original differential equation. The author gives some examples and a criterion for stability of integration methods. This criterion is then applied to some well-known integration formulas.—(22.1).

METEOROLOGY

Impingement of cloud droplets on a cylinder and procedure for measuring liquid-water content and droplet sizes in supercooled clouds by rotating multicylinder method. R. J. Brun, et al. N.A.C.A. Report 1215 (1955).

The amount of water impinging in droplet form, the area of impingement, and the rate of impingement per unit area on a cylinder surface are calculated from droplet trajectories and presented in terms of dimensionless parameters to cover a wide range of flight and atmospheric conditions. The rotating multicylinder method for in-flight determination of liquid-water content and droplet size is described.—(24).

Standard atmosphere-tables and data for altitudes to 65,000 *feet. N.A.C.A. Report* 1235 (1955).—(24 × 1·7).

MISSILES

Generalized trajectory curves for bodies moving in air. R. J. Templin and M. M. Callan. N.A.E. Laboratory Report L.R.-159. (*March* 1956).

A chart has been constructed which enables rapid development, using a step method, of trajectory curves having any initial values of the ratio initial velocity to terminal velocity, and the angle of the trajectory to the horizontal.—(25.2).

*Some recent aerodynamic techniques in design of fin-stabilized free-flight missiles for minimum dispersion. M. W. Hunter, et al. Douglas Report SM-*19532 (*January* 1955).

Design techniques have been developed, which permit appreciable reduction in dispersion by considering the conflicting stability requirements from internal and external disturbances.—(25.1).

POWER PLANTS

Development of an air injector. F. Cheers. N.R.C. Report MT-31 (March 1956).

An injector was designed and built to convert an air supply of 32 lb./sec. at 100 p.s.i. abs. to about 100 lb./sec. at 21 p.s.i. abs. for combustion work. Initial tests with the mixing pipe exhausting through a short diffuser to atmosphere showed that the design mass flow could be attained, but with a very high noise level, and with poor velocity distribution and very unsteady flow at the end of the mixing section. After some modification, with an experimental combustor rig providing a high pressure drop at the end of the mixing pipe, the performance was found to be reasonably close to that predicted by theory, with very good distribution and steady flow conditions at the test section.—(27.0).

Instabilités de la combustion dans les moteurs fusées; étude expéperimentale. M. Barrère, et al. O.N.E.R.A. Publication 82.

Technique expérimentale propre à l'étude des instabilités de combustion dans un moteur fusée. Exposé des méthodes de mesure et caractéristiques des propulseurs utilisés.—(27.3 × 34.1.2).

Some linear dynamics of two-spool turbojet engines. D. Novik. N.A.C.A. T.N. 3274. (June 1956).

Transfer functions, descriptive of the responses of inner- and outer-spool speed to changes in turbine-inlet temperature and exhaust-nozzle area, were derived analytically and corroborated experimentally.—(27.1).

Self shielding in rectangular and cylindrical geometries. H. Schneider, et al. N.A.C.A. T.N. 3661 (April 1956).

The steady-state diffusion approximation and the P_3 approximation of transport theory have been applied for a comparison of the neutron-flux distributions and self-shielding factors for multi-region cells of rectangular and cylindrical geometries. These cells represent a given arrangement of moderator, fuel, and cladding; usually considered to be homogeneous. The effects of chemical binding in the water region of the cells were also studied and the results were compared with the cases where chemical binding was neglected. An electromechanical differential analyser was used to solve the flux equations.—(27.5).

Performance and operational studies of a full-scale jet-engine thrust reverser. R. C. Kohl. N.A.C.A. T.N. 3665 (April 1956).

An axial-flow turbo-jet engine equipped with a hemispherical target thrust reverser was pylon-mounted beneath the wing of a cargo aeroplane.—(27.1.2).

PROPELLERS

Wake survey and strain gauge measurements on an inclined propeller in the R.A.E. 24 ft. tunnel. Part II. Comparison of measured and calculated 1P stresses. R. Doust and E. J. Hellier. C.P. 228 (1956).—(29.7).

SCIENCE—GENERAL

Diffusion centrale des rayons X par les métaux. J. Blin. Pub. sc. et tech. No. 311 (1956).—(32.2.1 × 21.6.1).

STRUCTURES

Loads

See also Theory and Analysis

Turbulence encountered by Comet I aircraft. J. R. Heath-Smith. C.P. 248 (1956).

Acceleration records have been obtained of the turbulence encountered by B.O.A.C. Comet aircraft in 680,000 miles of operational flying on routes connecting London with South Africa and the Far East. It is shown that turbulence decreases with increasing altitude. Of all gusts greater than 10 ft./sec. E.A.S. 91 per cent. were encountered below 27,500. Above 27,500 ft. about 75 per cent. of gusts greater than 10 ft./sec. E.A.S. occur in cumuliform cloud. In flight sectors where conditions favour the formation of cumuliform cloud, gusts may be several times more numerous on average than over widespread routes.—(33.1.1).

Low-speed yawed-rolling characteristics and other elastic properties of a pair of 26-inch-diameter, 12-ply-rating, type VII aircraft tires. W. B. Horne, et al. N.A.C.A. T.N. 3604 (May 1956).

The low-speed (up to 2 miles per hour) cornering characteristics of two 26 × 6·6, type VII, 12-ply-rating tyres under straight-yawed rolling were determined over a range of inflation pressures and yaw angles for two vertical loads. The cornering characteristics of one tyre rolling along circular paths of different radii were investigated for one condition of vertical load and inflation pressure. Static tests were also performed to determine the vertical, lateral, torsional, and fore-and-aft elastic characteristics of the tyres. —(33.1.2).

The accuracy of the substitute-stringer approach for determining the bending frequencies of multistringer box beams. W. W. Davenport. N.A.C.A. T.N. 3636 (April 1956).

The accuracy of the substitute-stringer approach for including the effects of shear lag in the calculation of the transverse modes and frequencies of multi-stringer box beams is investigated. Box beams, the covers of which consist of normal-stress-carrying stringers on sheets which carry not only shear but also normal stress, are analysed exactly. Frequencies of beams with various numbers of stringers, obtained by means of this exact analysis, serve to determine the possible accuracy of the frequencies obtained by the substitute-stringer approach.—(33.1.2 × 33.2.4.1.10).

Theory and Analysis

See also Loads

The influence of pre-loading on the fatigue life of aircraft components and structures. R. B. Heywood. C.P. 232 (1956).

Tests on aircraft components and structures are described which show that pre-loading can have a marked influence on fatigue behaviour. Tensile pre-loading may increase the life—in one instance a hundredfold improvement was obtained—and compressive pre-loading may reduce the life. The effect is attributed to residual stresses and to load redistributions induced by pre-loading.—(33.2.4.0.10).

Investigation of the fatigue of extruded tubular booms. W. A. P. Fisher and H. Yeomans. C.P. 234 (1956).

Earlier tests on Viking tubular spar booms having shown considerable scatter and low fatigue strength, a special programme of tests was undertaken in order to ascertain the cause. Three types of specimen made from Aluminium Alloy Extruded Tube to Materials Specification D.T.D.364, were tested and the results compared.—(33.2.4.0.10).

The buckling under longitudinal compression of a simply supported panel that changes in thickness across the width. E. C. Capey. C.P. 235 (1956).

An exact solution is obtained for the buckling under longitudinal compression of a simply-supported panel made up of three strips in which the central strip differs in thickness from the outer strips. The critical buckling stress is calculated numerically for a number of different ratios between thicknesses and widths of the central and outer strips. Some comparative results are given for the case when the longitudinal edges are clamped.—(33.2.4.6.6).

Optimum designs for reinforced circular holes. E. H. Mansfield. C.P. 239 (1956).

The design of reinforced circular holes in an infinite sheet is considered theoretically. The stress system in the main body of the sheet is assumed to be one in which the principal stresses are in the ratio $1:-1$ (*i.e.* shear), $1:0$ (*i.e.* tension), $1:1$ or $1:\frac{1}{2}$. The reinforcement may vary round the hole and families of such reinforcements with constant total weight are considered: the peak stresses in the sheet are evaluated so that optimum weight-strength designs are determined.—(33.2.4.6.0).

Relative accuracy of deflections and bending moments (or stresses) derived by the method of R.A.E. Report No. Structures 168. D. Williams. C.P. 254. (1956).

The relative accuracies of moments and deflections, as derived by the method of R.A.E. Report Structures 168, are discussed, and it is shown that moments are not expected in general to be less accurate than the deflections.—(33.2.1).

Influence of large amplitudes on flexural motions of elastic plates. G. Herrmann. N.A.C.A. T.N. 3578. (*May* 1956).

A non-linear plate theory of motion, valid for large deflections, is developed and discussed in the light of other theories. The influence of large rotations is demonstrated by solution of the resulting equations for the case of straight-crested waves. A study is made of the origin of certain terms appearing in non-linear plate theories.—(33.2.4.5.10 × 33.1.2).

Results of axial-load fatigue tests on electropolished 2024-*T*3 *and* 7075-*T*6 *aluminum-alloy-sheet specimens with central holes. C. B. Landers and H. F. Hardrath. N.A.C.A. T.N.* 3631 (1956).

Results are presented of axial-load fatigue tests at stress ratios of 0 and −1·0 on electro-polished 2024-T3 (24S-T3) and 7075-T6 (75S-T6) aluminium-alloy-sheet specimens with central holes. The specimen widths and hole diameters were varied to provide data suitable for a study of notch-size effect. The data are compared with previously published results of tests on unnotched electro-polished specimens and on unpolished specimens containing central holes.—(33.2.4.5.10×21.2.2).

Analysis of the ultimate strength and optimum proportions of multiweb wing structures. B. W. Rosen. N.A.C.A. T.N. 3633 (1956).

A structural-efficiency analysis of multiweb wing structures is presented. Minimum structural weight is shown as a function of the design variables in a manner which makes comparisons possible with structures of different materials or with other types of construction. The structural-efficiency chart presented is based on equations developed to relate ultimate bending strength of multiweb beams which fail in the local buckling mode to beam proportions and material properties and is substantiated by the results of multiweb-beam bending tests.—(33.2.4.1).

A theory for the elastic deflections of plates integrally stiffened on the one side. R. F. Crawford. N.A.C.A. T.N. 3646 (*April* 1956).

An elastic-deflection theory is presented for anisotropic plates which exhibit coupling between bending and stretching. In particular, the theory provides a basis for analysing plates integrally stiffened on one side. The effect of coupling is responsible for the presence of added terms in the potential-energy expression, the small- and large-deflection equations of equilibrium, and the boundary conditions which do not occur in ordinary plate theory. Example calculations show that, in the case of a simply supported square plate loaded in compression and having equal flexural stiffnesses in the principal directions, coupling may significantly lower the inplane compressive load at which deflections grow rapidly.—(33.2.4.6.1).

Investigation of the compressive strength and creep lifetime of 2024-*T aluminum-alloy skin-stringer panels at elevated temperatures. E. E. Mathauser and W. D. Deveikis. N.A.C.A. T.N.* 3647 (*May* 1956).

The experimental results of an investigation to determine compressive strength and creep lifetime of 2024-T (formerly 24S-T) aluminium-alloy skin-stringer panels at room temperature and at 400° F are presented. The results of strength tests at room temperature and 400° F are compared with predicted strength obtained from methods given in the literature for estimating crippling strength of short panels and for predicting column strength of longer panels. Creep lifetime curves are presented for four values of slenderness ratio and creep characteristics of the panels are discussed. A method which makes use of isochronous compressive stress-strain curves for predicting creep lifetime of panels is presented.—(33.2.4.6.9).

Fatigue crack propagation in severely notched bars. W. S. Hyler, et al. N.A.C.A. T.N. 3685. (*June* 1956).

Fatigue tests were made in rotating bending on severely notched bars machined from 2024-T4 aluminium-alloy extruded round rods. Two sizes of specimens were studied, ¼ in. diameter and 2 in. diameter specimens. The smaller specimens were notched with a V-groove and had notch severities K_t of 5·2. The larger specimens also contained V-grooves with notch severities of 5·2 and 13·9.—(33.2.4.13.10 × 21.2.2).

STRUCTURES

Testing

See also Materials

Some work on tension pads for structural tests. J. K. Oaks and P. B. Hovell. C.P. 238 (1956).

Sorbo rubber tension pads glued with Bostik adhesive have been developed for loading aircraft components during static and fatigue strength tests. The gluing technique, detail tests and pilot test on a typical component are described. A safe working stress for this type of pad is suggested. An account is given of some component approval tests in which tension pads were used.—(33.3.1).

THERMODYNAMICS

See also Power Plants

Étude expérimentale de la convection forcée de la chaleur a partir de cylindres a surface rugueuse. E. Brun, et al. Pub. sc. et tech. N.T. 60 (1956).

Étude de la convection forcée de la chaleur sur la surface extérieure de cylindres circulaires. L'étude, d'abord faite avec des surfaces lisses, conduit aux résultats déjà donnés dans la littérature.—(34.3.2).

Experimental investigation of free-convection heat transfer in vertical tube at large Grashof numbers. E. R. G. Eckert and A. J. Diaguila. N.A.C.A. Report 1211 (1955).

Local free-convection heat-transfer coefficients and temperature fields in the turbulent flow range were obtained within a vertical, stationary tube closed at the bottom, heated along its walls, and having a length-to-diameter ratio of 5. Convective heat-transfer coefficients were correlated by the general relations for free-convection heat transfer. (This report supersedes R.M. E52F30).—(34.3.2).

Thermodynamic properties of gaseous nitrogen. H. W. Woolley. N.A.C.A. T.N. 3271 (*March* 1956).

The N.B.S.-N.A.C.A. tables of thermal properties of gaseous nitrogen are grouped together in this report for convenient use. They include the thermodynamic functions for the gas, both real and ideal, the transport properties for the gas, and the vapour pressure of the liquid and the solid. The tables are in dimensionless form and conversion factors to frequently used units are given. Deviation plots or tables indicating the agreement or discordance of the experimental data are included.—(34.1).

Vapor-phase oxidation and spontaneous ignition-correlation and effect of variables. D. E. Swarts and M. Orchin. N.A.C.A. T.N. 3579 (*April* 1956).

The spontaneous ignition temperatures of eight structually different hydrocarbons were determined and correlated with the behaviour of the same hydrocarbons toward vapour-phase oxidation.—(34.1.1).

Method of calculating core dimensions of crossflow heat exchanger with prescribed gas flows and inlet and exit states. E. R. G. Eckert and A. J. Diaguila. N.A.C.A. T.N. 3655 (*April* 1956).

A calculation procedure is presented for determining the dimensions of a heat-exchanger core with a prescribed heat-transfer surface. The procedure is applicable when the gas-flow quantities as well as the inlet and outlet gas conditions on both sides of the heat exchanger are specified. The procedure is applied to a numerical example.—(34.3).

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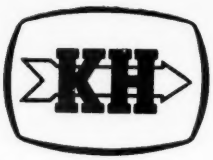

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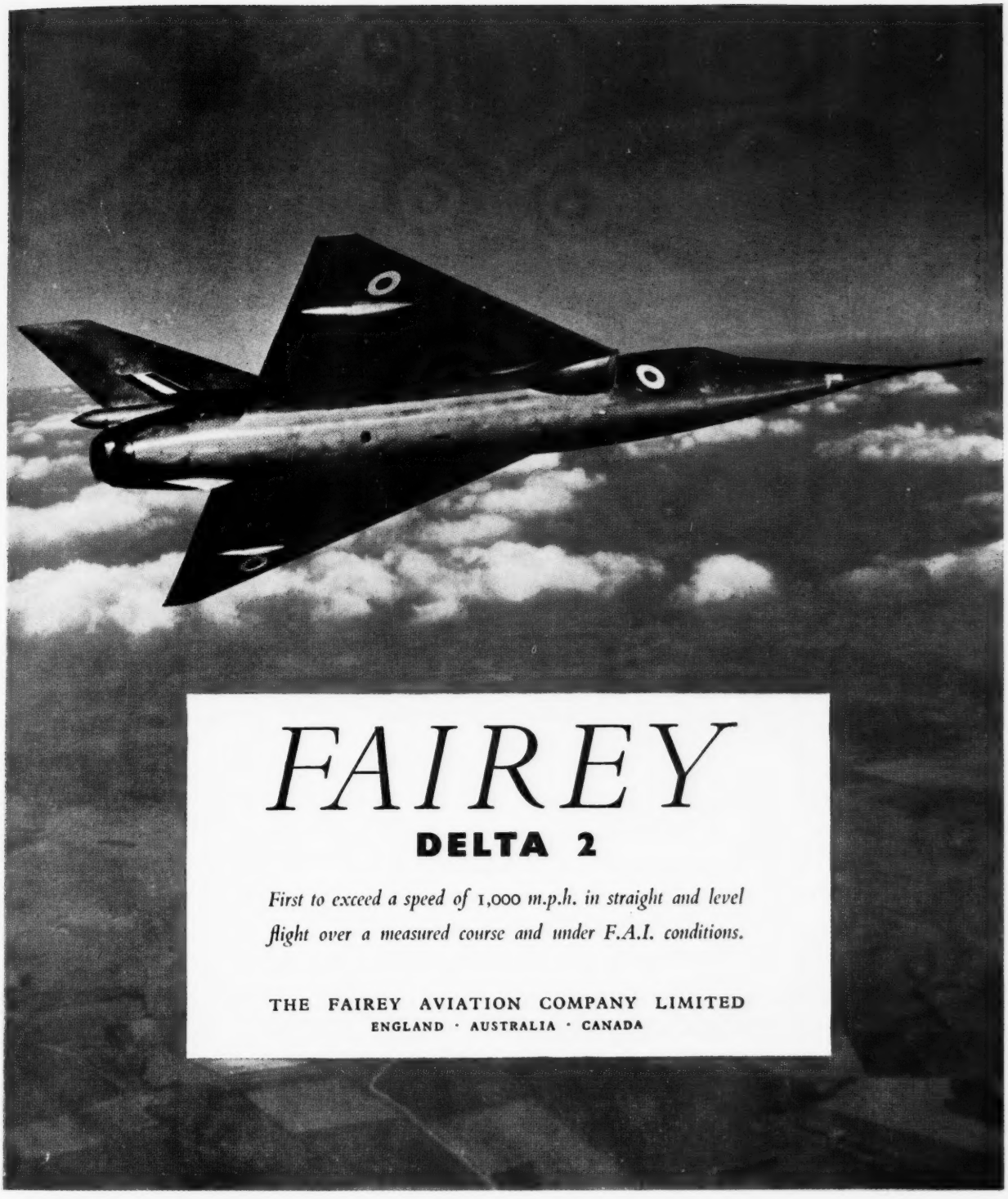
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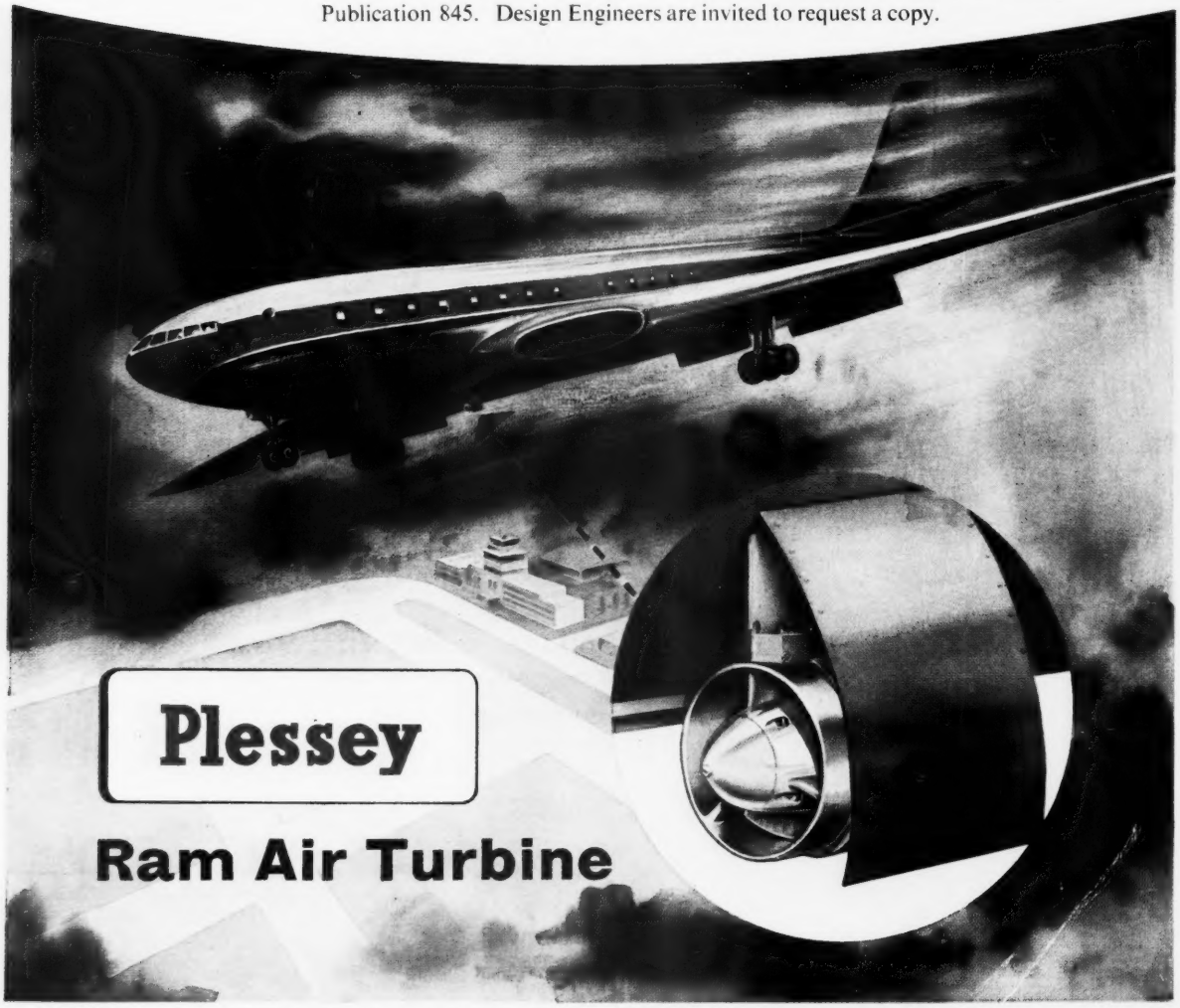

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